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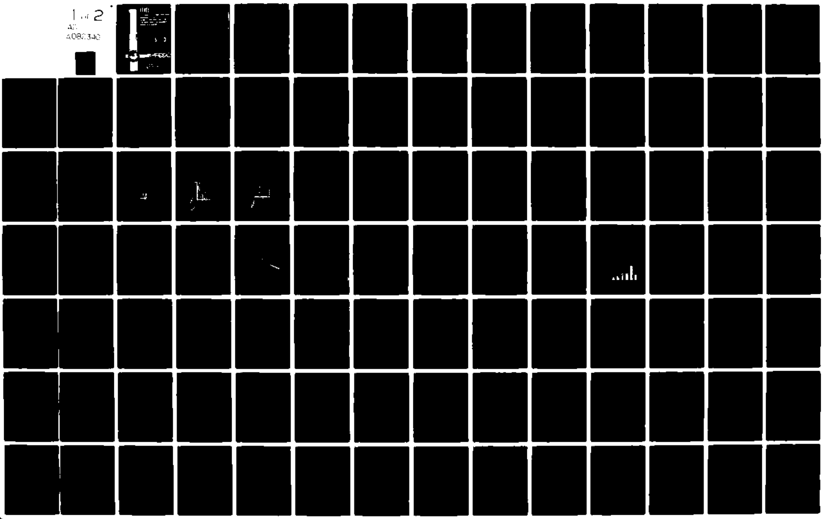

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Statistical prediction models for pavement condition index (PCI) and key distresses have been developed for asphalt and jointed concrete pavements. The models were developed based on field data collected during FY76 through FY78 from 19 airfields throughout the United States. The field data included traffic, climate, pavement structure and material properties, and previous maintenance. Prediction models were developed for concrete and asphalt pavements, respectively. These models represent the first iteration of the con-

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sequence models needed to help pavement engineers select the most economical maintenance and repair (M&R) strategies and to help management efficiently allocate repair funds.

Two workshops were held to determine information required by Air Force Command and Base engineers to efficiently manage airfield pavement M&R. The workshops were attended by many Command and Base engineers, as well as representatives from the Air Force Design Center and the Directorate of Management Systems. Computer and information requirements were defined and implementation alternatives for a computer-aided pavement management system were developed as a result of these workshops.

PREFACE

This report documents work accomplished by the U.S. Army Construction Engineering Research Laboratory under Project DTC-8-128 from the Air Force Engineering and Services Center (AFESC), Tyndall AFB, FL. Mr. Mike Womack was Project Engineer for AFESC.

This report has been reviewed by the Public Affairs Office (PA) and is releasable to the National Technical Information Service (NTIS). At NTIS it will be available to the general public, including foreign nations.

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This technical report has been reviewed and approved for publication.

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SECTION I

INTRODUCTION

BACKGROUND

Selecting the most economical maintenance and repair (M&R) alternative that satisfies all constraints is one of the major responsibilities of the airfield pavement engineer. To accomplish this task satisfactorily, the engineer must have extensive knowledge of the consequence of applying various M&R alternatives, as well as the consequence of not applying any M&R. This requires the ability to predict future pavement condition. The development of this capability is extremely difficult because of the many designs, materials, climates, subgrades, repair alternatives, and amounts of traffic.

Efforts to develop analytical methods of predicting pavement condition were begun during FY77 with a preliminary study which concluded that it was feasible to predict condition using probabilistic theory and empirical models developed from field data (Reference 1). Pavement "condition" was specifically defined as the trend of the Pavement Condition Index (PCI) over time, and the development of major distress types over time. The PCI is a composite index that represents the pavement's structural integrity and operational surface conditions (References 1 through 5). It has been adopted by the U.S. Air Force and is now being fully implemented. The PCI, along with distress prediction, can be used to determine M&R needs. Thus, if the PCI and major distress types can be reasonably predicted over a future time period for a variety of pavement situations, the consequence of various M&R alternatives can be predicted.

The types of questions that M&R consequence models should be able to answer about a given pavement feature are:

1. If only routine maintenance is applied over the next X number of years, what are the consequences in terms of PCI, distress occurrence, costs, and downtime (Figure 1)?

2. If particular types of major maintenance (such as slab replacement and patching) are applied, what are the consequences (Figure 2)?

3. If an overlay or recycling is performed, what are the consequences (Figure 3)?

4. If a mission change occurs, what are the consequences of applying or not applying specific M&R (Figure 4)?

The use of consequence models will require the engineer to gather a considerable amount of data and to perform many computations, especially if many pavement sections are analyzed at one time. Therefore, it was necessary to study the feasibility of developing a pavement management information system.

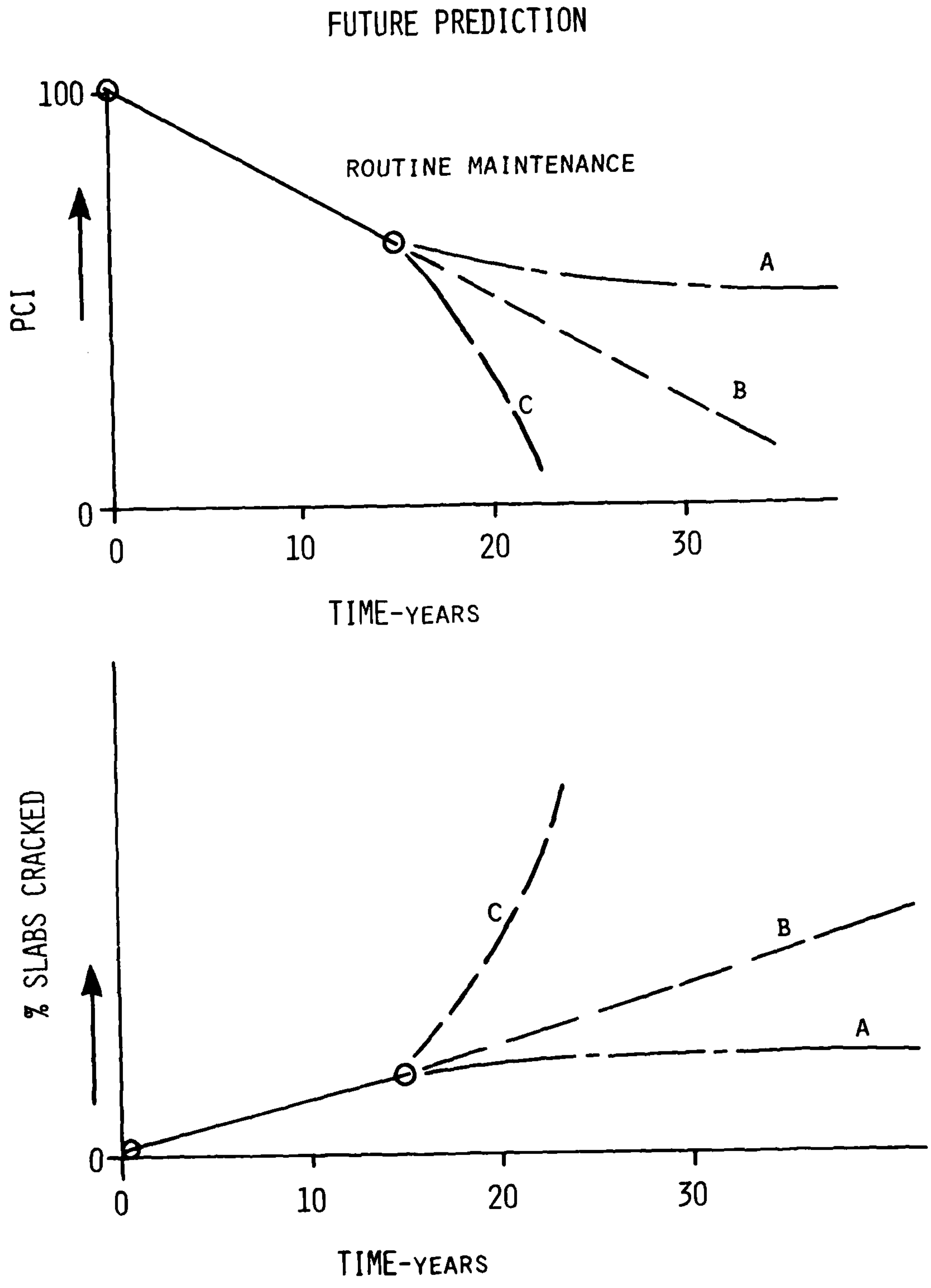


Figure 1. Schematic Design Showing Effect of Routine Maintenance on PCI and Distress Over Time.

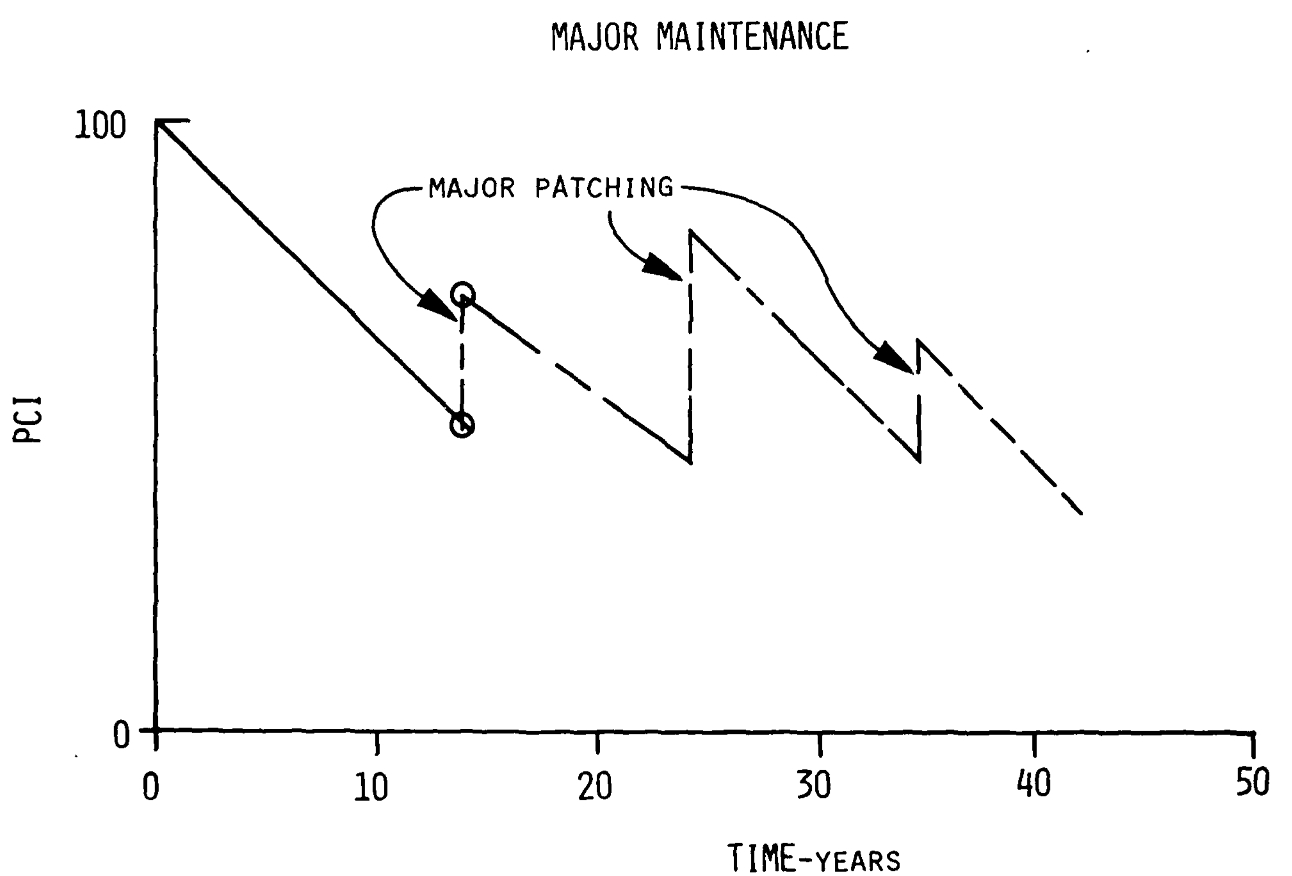


Figure 2. Schematic Diagram Showing Effect of Major Maintenance on PCI Over Time.

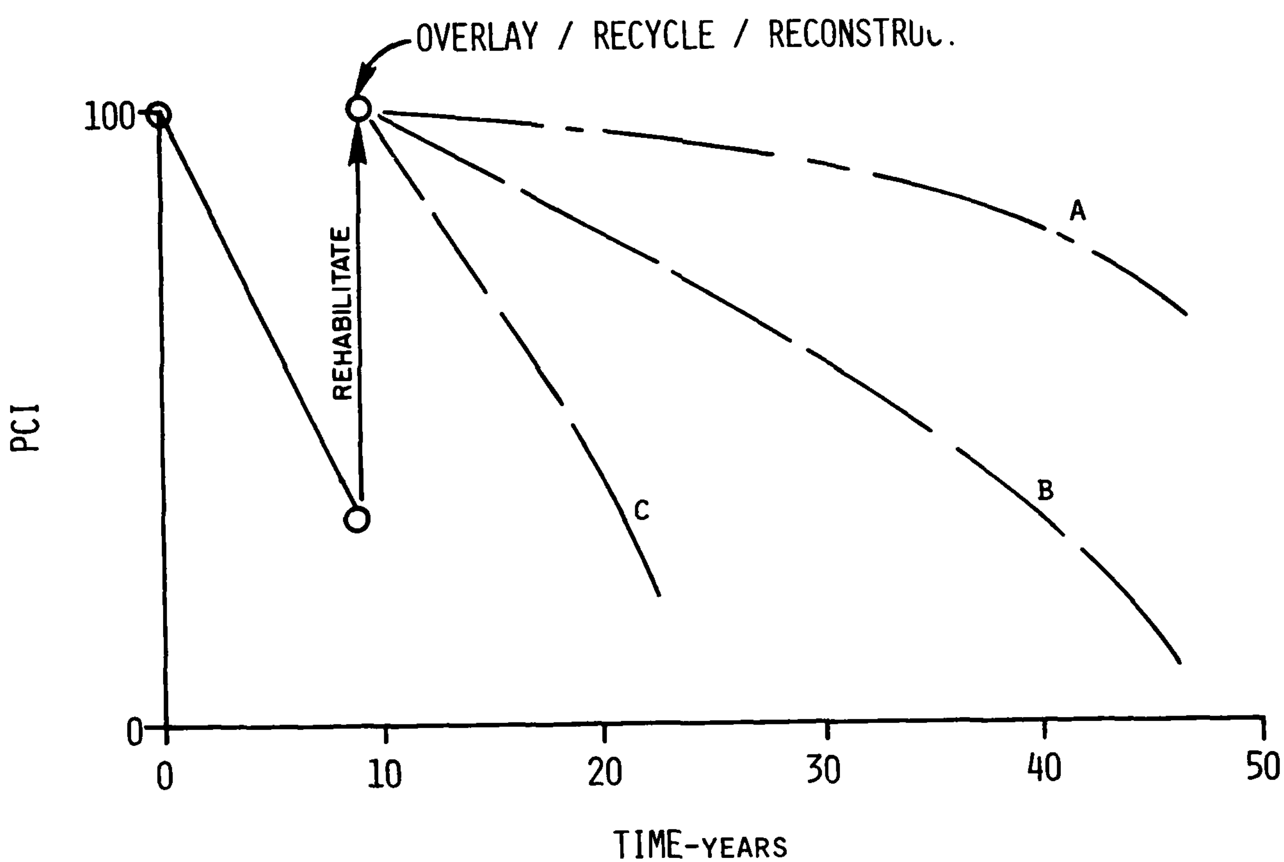


Figure 3. Schematic Diagram Showing Effect of Overall Repair on PCI Over Time.

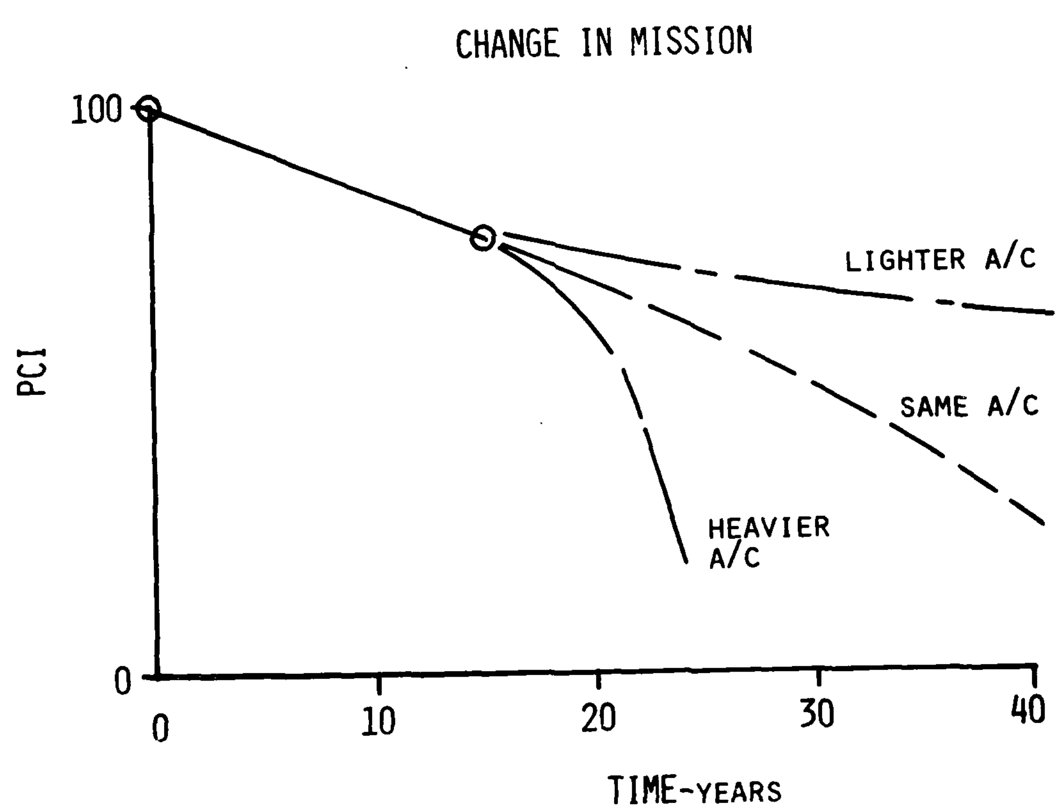


Figure 4. Schematic Diagram Showing Effect of Change in Mission Aircraft (A/C) on PCI Over Time.

Such an information system would insure expedient access to data required for using the consequence models and for performing other management requirements, such as project validation, estimation, and optimization.

OBJECTIVES

The objectives of the FY78 work effort were:

1. To develop models for predicting the PCI of asphalt and concrete pavements, including both asphalt and concrete overlays using available data

2. To develop models for predicting key load-associated distress types for asphalt and concrete pavements using available data

3. To determine information requirements for pavement management

4. To provide alternatives for implementing a computer-aided pavement management system.

APPROACH

The above objectives were achieved as follows:

1. Data were collected from many concrete and asphalt airfield features to provide a data base from which to derive prediction models. Condition data were obtained from numerous surveys conducted over the past 3 years at U.S. Air Force bases, and physical data were obtained from historical records.

2. Multiple regression techniques were used to develop prediction models for PCI and distress, using this data base. Sensitivity analyses were conducted to determine the usefulness of the models. There were not adequate data to develop comprehensive models, so additional data collection will be necessary; therefore, the existing models should be considered tentative.

3. A workshop was held with a number of major command and base pavement engineers to determine information requirements for pavement management and to help select alternatives for implementing computer-aided pavement management.

ORGANIZATION

This report is divided into two parts. Part I discusses the development of M&R consequence models and describes the data base from which the various models were derived (Section II). Sections III and IV discuss the development of PCI and distress prediction models for concrete and asphalt pavements, respectively. Part II contains information requirements for pavement management. Section VI describes the information requirements for pavement management, and Section VII describes various alternatives for implementation of a computer-aided pavement management system.

PART I

MAINTENANCE AND REPAIR CONSEQUENCE MODELS

DESCRIPTION OF DATA USED TO DEVELOP MODELS

Airfield pavement data were obtained from 19 U.S. Air Force bases throughout the United States (see Figure 5). The data consisted of detailed distress information (including PCI) obtained during surveys conducted by the authors during FY76 to FY78, and historical information (i.e., material, traffic, design, and climate data). These data were obtained primarily from pavement evaluation reports and direct contact with base and major command pavement engineers. In addition to the raw data, several new variables were created that combined the effect of two or more of the raw data variables (such as the stress/strength ratio and the load repetition factor). This section briefly describes the data base used to develop the PCI and distress models presented in Sections III and IV.

It is important to note that the reliability and range of applicability of the empirical models depend largely on the data base from which they were derived. Thus, the limitations and deficiencies of the data base are described.

CONCRETE PAVEMENT DATA (NO OVERLAYS)

Concrete pavements were surveyed at all of the airfields shown in Figure 5, except Eielson, Fort Wainwright, Craig, Eglin, and Pope Air Force Bases. The surveys were conducted during the development and validation of the PCI procedure and also during training and implementation sessions held at various bases. A total of 76 concrete pavement features* were surveyed, and after initial examination of the data, 67 features were retained for analysis. Nine features were deleted because several data items (such as modulus of rupture) could not be obtained. The following subsections describe the physical characteristics of the pavement features.

Feature Type and Usage

Runways (25 features), taxiways (22 features), and aprons (20 features) were surveyed. Fifty-eight of the features were considered as primary pavements, and nine were considered as secondary pavements.

Traffic

Light-, medium-, heavy-load aircraft currently used in the Air Force were used at the airfields (see Table 1). The data in the table show that a large majority of the pavement features had light-load traffic. The aircraft assigned to a particular feature was the most critical aircraft regularly using

* Pavement with the same construction history, having the same structure, and subjected to the same traffic.

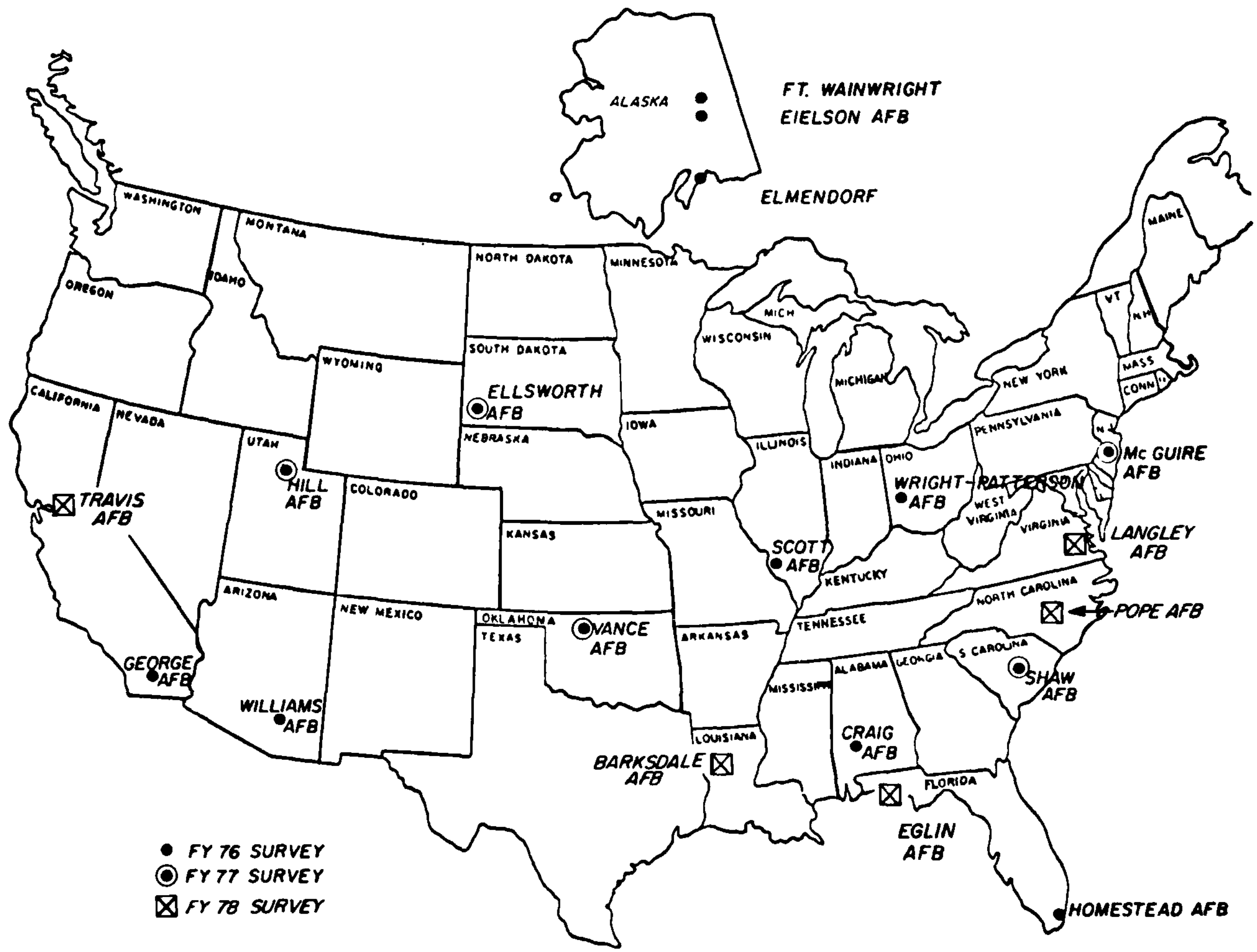


Figure 5. Airfields From Which Data Were Collected for Development of Prediction Models.

TABLE 1. SUMMARY OF TRAFFIC AT AIRFIELDS

	No. of Pavement Features		
Airfield	Light* Load	Medium** Load	Heavy+ Load
Langley	19	1	--
Barksdale	--	1	--
Wright-Patterson	--	--	4
George	2	--	--
McGuire	1	2	--
Williams	3	--	--
Hill	1	2	--
Vance	18	--	--
Ellsworth	--	--	6
Shaw	4	--	--
Homestead	1	--	--
Travis	--	2	--
Totals	49	8	10

*Primarily trainers and fighters
**Primarily C-141, C-130, DC-8, KC-135, C-9
+B-52

the pavement. This was difficult for a few features because there was mixed traffic. For example, if a feature was being used regularly by both light- and medium-load aircraft, the medium-load aircraft would be assigned. If very few medium-load aircraft used the feature, the light-load aircraft would be assigned. The maximum gross weight was used for each aircraft to calculate stresses in the slab. Traffic areas were designated as A (9 features), B (43 features), and C (15 features).

Slab Thickness

Table 2 shows the distribution of slab thickness, which ranges from 6 to 22 inches, with a mean thickness of 12.3 inches.

Joint Spacing

Table 3 shows the range of joint spacing. Approximately half the features have 25- x 25-foot slabs, and the slabs range from 12.5 x 12.5 feet to 25 x 25 feet.

Concrete Modulus of Rupture

The concrete modulus of rupture ranged from 520 to 922 psi, with a mean of 739 psi.

Foundation Support

The modulus of subgrade reaction ranged from 30 to 500 psi, with a mean of 163 psi. Soil types ranged from fine-grained clay and silt to granular. The slab subbase was granular in all cases, with a mean thickness of 5.9 inches.

Age of Construction

The age of the pavement from time of construction to the date of the condition survey ranged from 2 to 34 years, with an overall mean of 19 years. A histogram of age is shown in Figure 6.

Maintenance

The only two maintenance activities included were slab replacement and patching (more than 5 square feet each). These variables were quantified as the percentage of slabs replaced and the percentage of slabs patched. Their ranges and means were:

	Range	Mean
Slab Replacement (Percent Slabs)	0 to 23.5	3.1
Patching (Percent Slabs)	0 to 19.0	2.5

TABLE 2. FEATURE SLAB THICKNESS

Slab (Inches)	No. Features
6	10
7	1
8	1
9	6
10	11
11	7
13	3
14	2
15	4
16	13
18	5
19	2
22	2

TABLE 3. FEATURE JOINT SPACING

Length (Inches)	Width (Inches)	No. Features
12.5	12.5	6
15	12.5	6
15	15	1
20	12.5	12
20	20	3
25	12.5	3
25	20	2
25	25	34
		Total 67

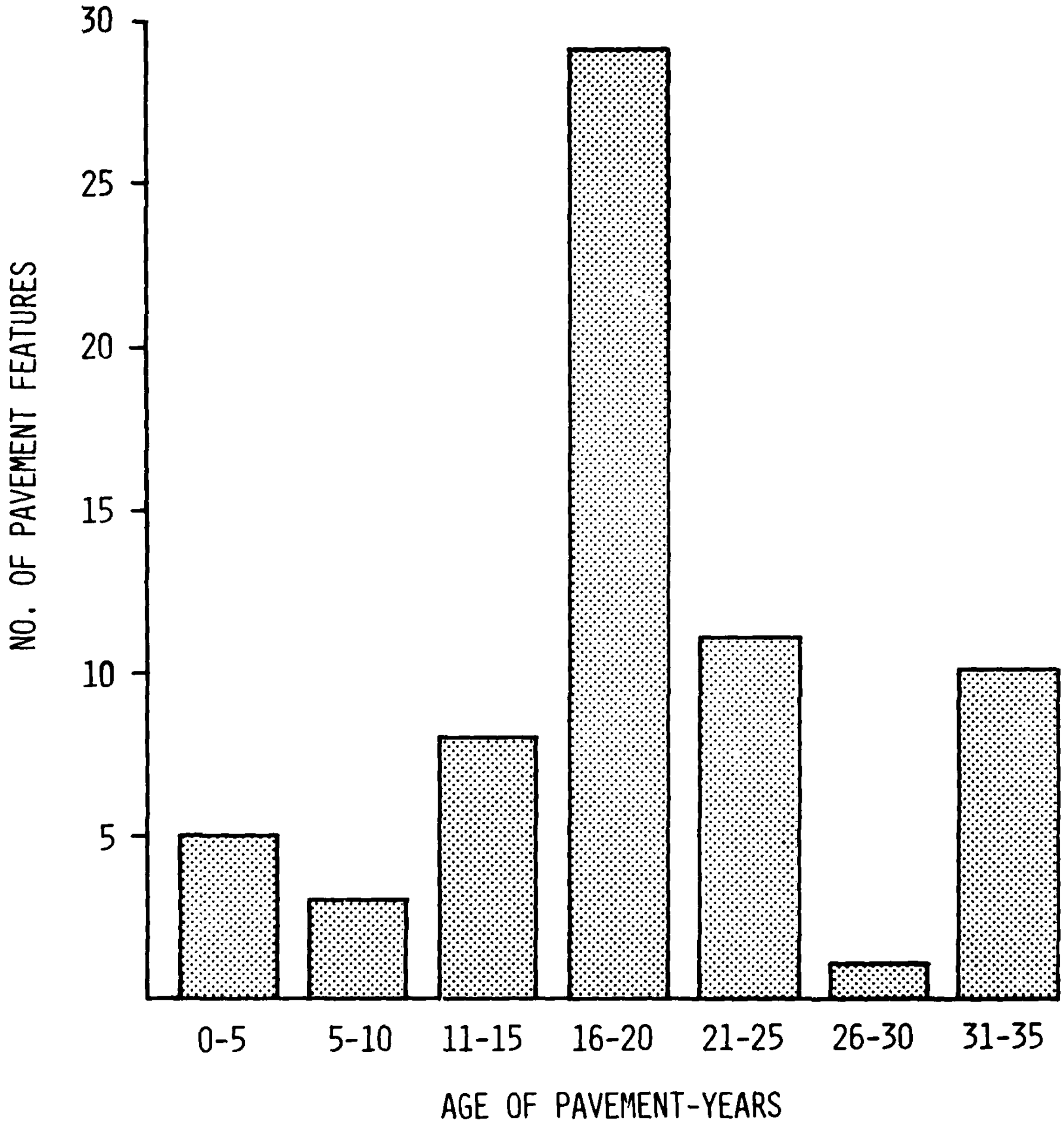


Figure 6. Frequency Distribution of Age of Concrete Pavements (No Overlays).

Climate

Climate was characterized by freezing index, average annual precipitation, and average annual temperature. The ranges and means of these variables were:

	Range	Mean
Freezing Index (degree days below 32°F)	0 to 678	99
Precipitation (inches)	3.5 to 56	30.7
Average Annual Temperature (°F)	46 to 75	58.3

Fatigue Stress/Strength Ratio

A variable was created by dividing the stress determined for an interior loading condition of the critical aircraft by the concrete's modulus of rupture. The stress was determined using charts which are based on stress charts prepared by the Portland Cement Association (PCA) computer program (Reference 6). The PCA program is based on the Pickett and Ray influence charts (Reference 7). These stress charts are given as Figures 7, 8, and 9 for single, dual, and dual-tandem gears, respectively. The stress/strength (or modulus of rupture) ratio varied from 0.15 to 0.80, with a mean of 0.37. Figure 10 is a histogram showing the distribution of the stress/strength ratio. This variable is multiplied by 100 and called FAT* (see Section III).

Pavement Condition Index (PCI)

The distress data collected during the condition surveys were used to compute the mean PCI of each feature, using the standard procedures described in Air Force Civil Engineering Center (AFCEC) Technical Report (TR) 44 (Reference 5). The mean PCI was computed from individual sample units selected and surveyed according to these standard procedures. However, for nine of the features, the PCI was obtained from a single sample unit selected randomly from the feature. The PCI ranged from 36 to 97, with a mean of 70.6. Figure 11 is a histogram of the PCI data. A large proportion of the features had PCIs ranging from 56 to 85, i.e., a Good to Very Good rating. Therefore, when additional data are collected, it is better to have a greater proportion of features with lower PCIs to provide a more balanced data set.

Slab Cracking

The percentage of slabs containing corner breaks, longitudinal and transverse cracks, and those in a shattered condition was computed for each feature. The mean percentage of cracked slabs was 16.6, with a range of 0 to 71 percent.

*Fatigue

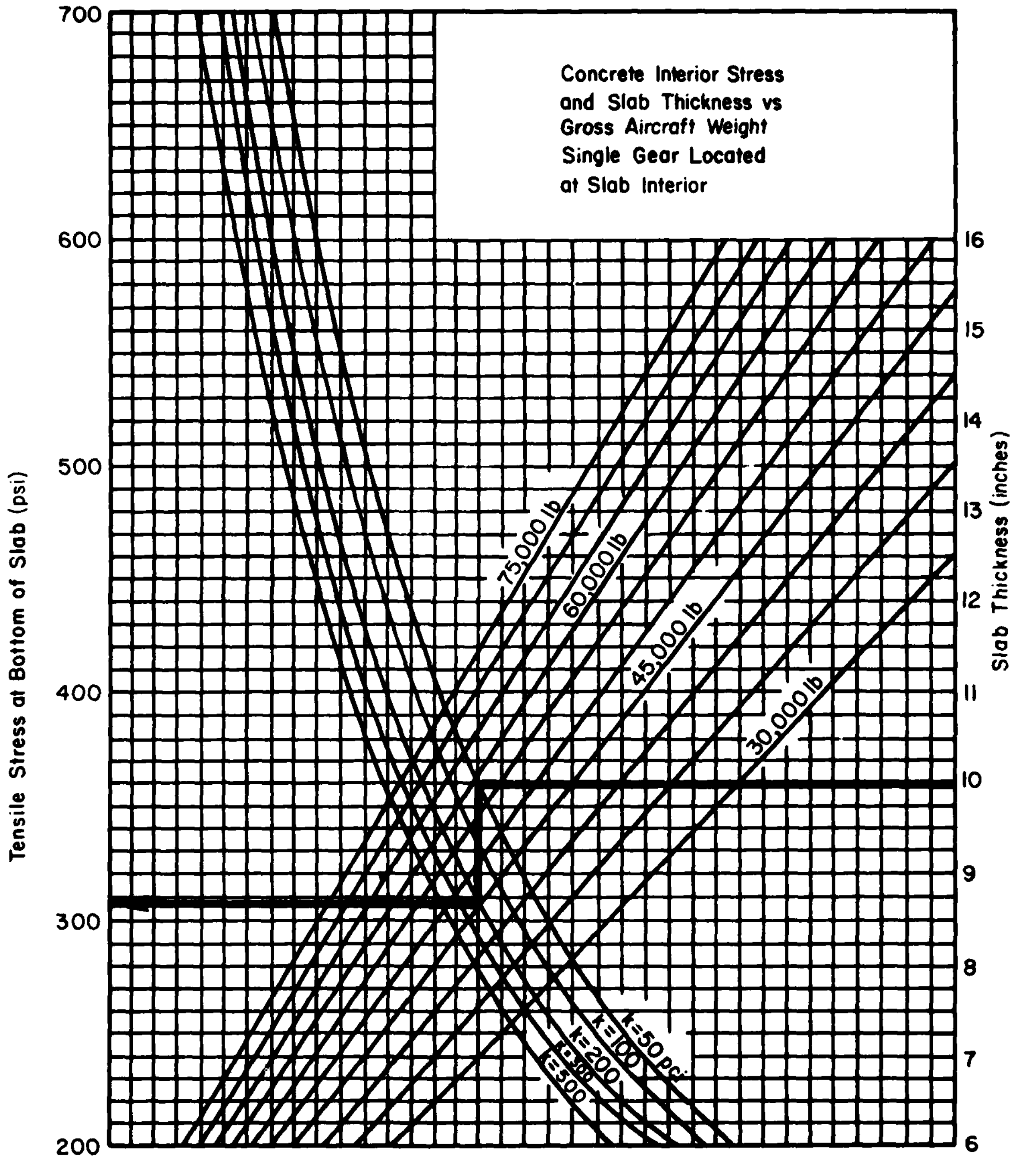


Figure 7. Chart for Obtaining the Tensile Stress at the Bottom of the Slab for a Single Wheel Gear Load.

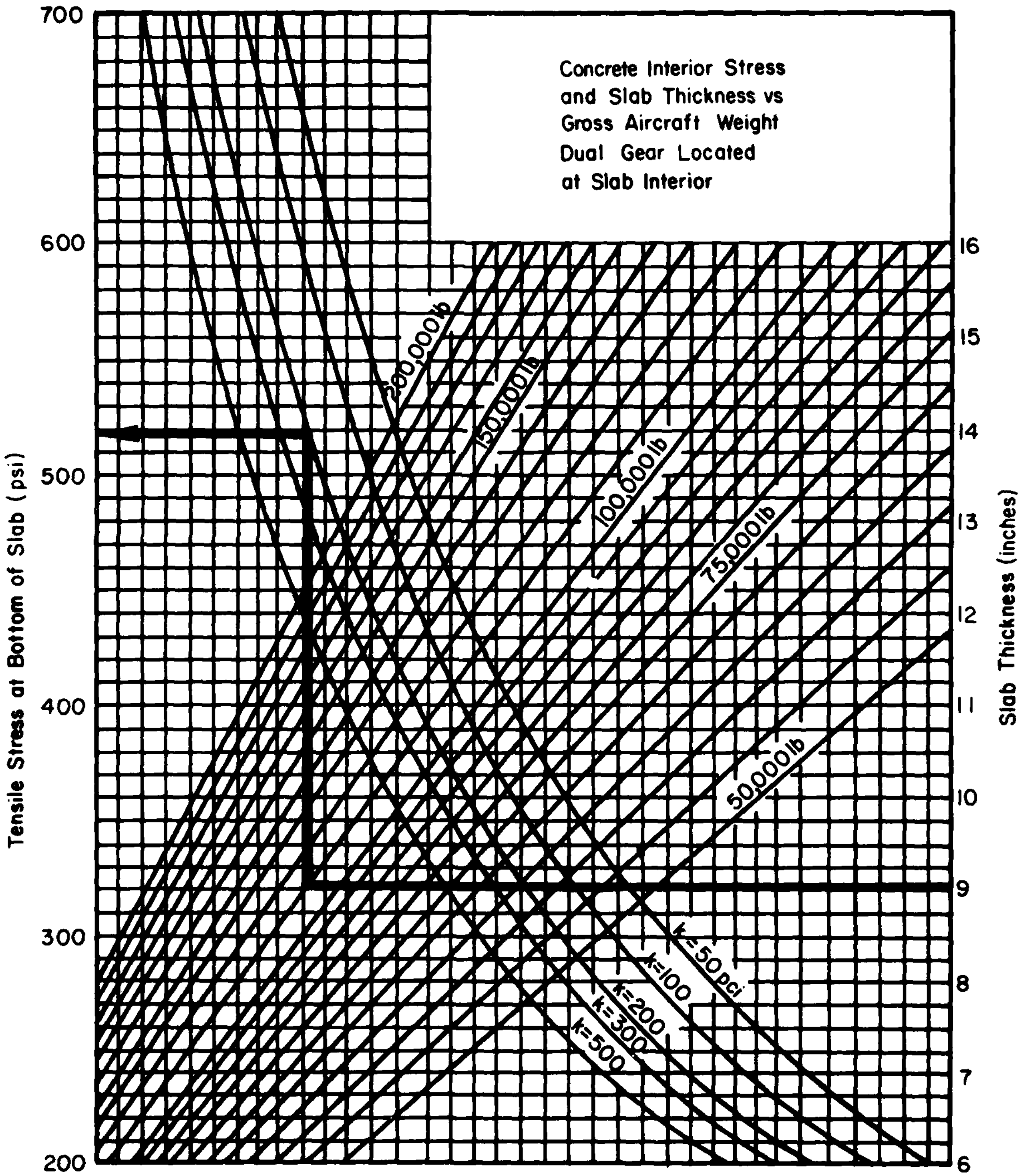


Figure 8. Chart for Obtaining the Tensile Stress at the Bottom of the Slab for a Dual Gear Load.

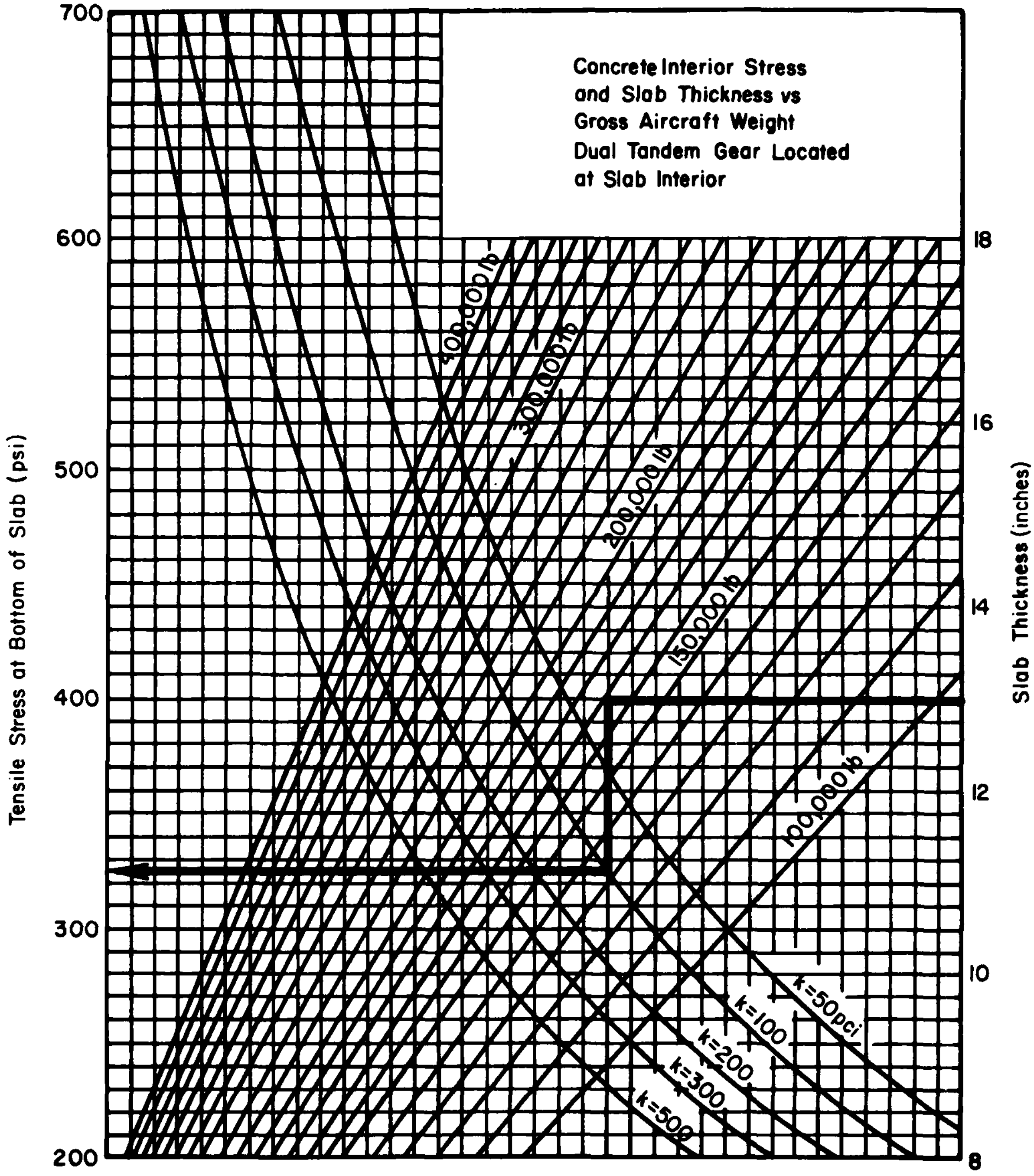


Figure 9. Chart for Obtaining the Tensile Stress at the Bottom of the Slab for a Dual Tandem Gear Load.

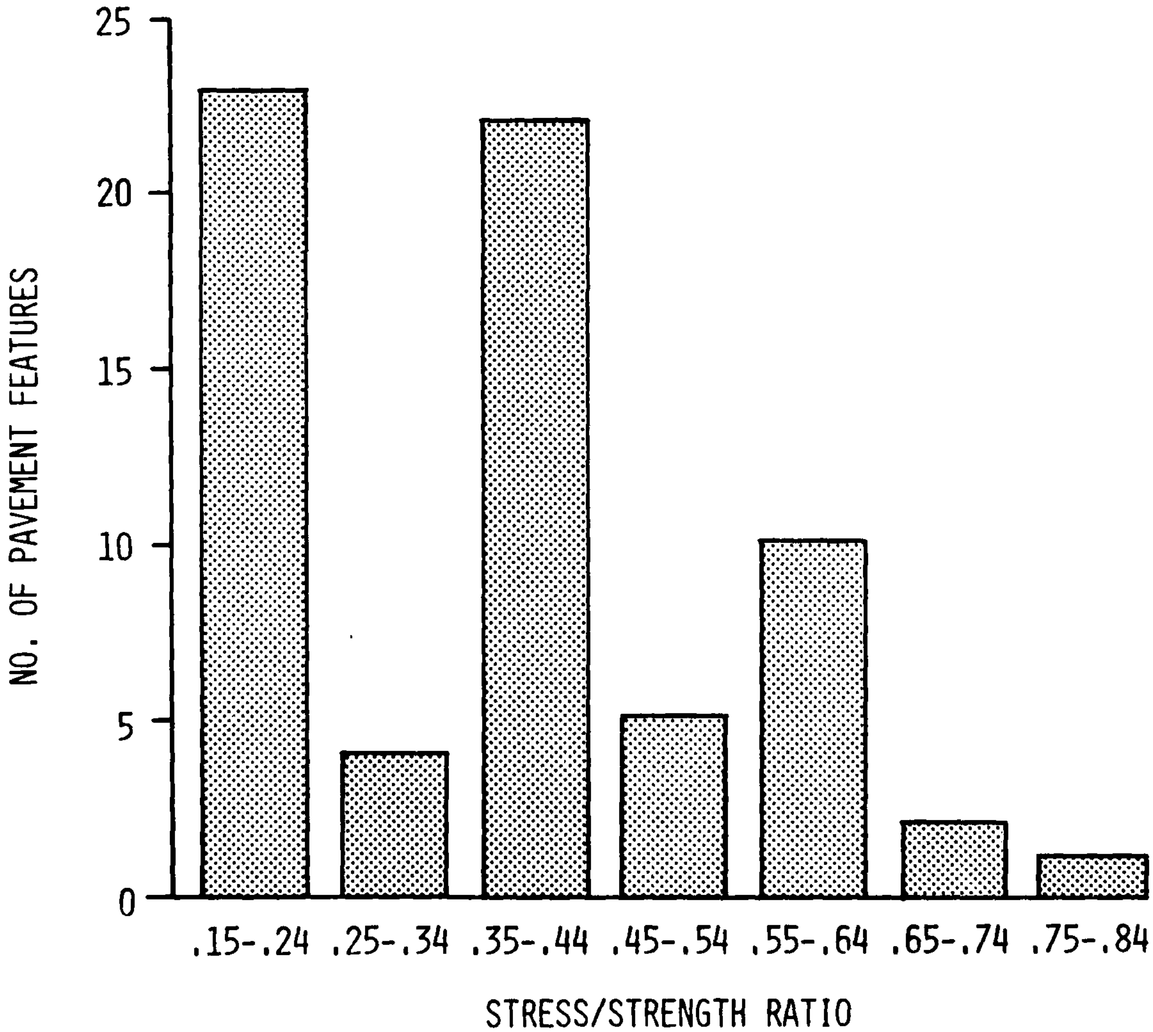


Figure 10. Frequency Distribution of Stress/Strength Ratio for Concrete Pavements.

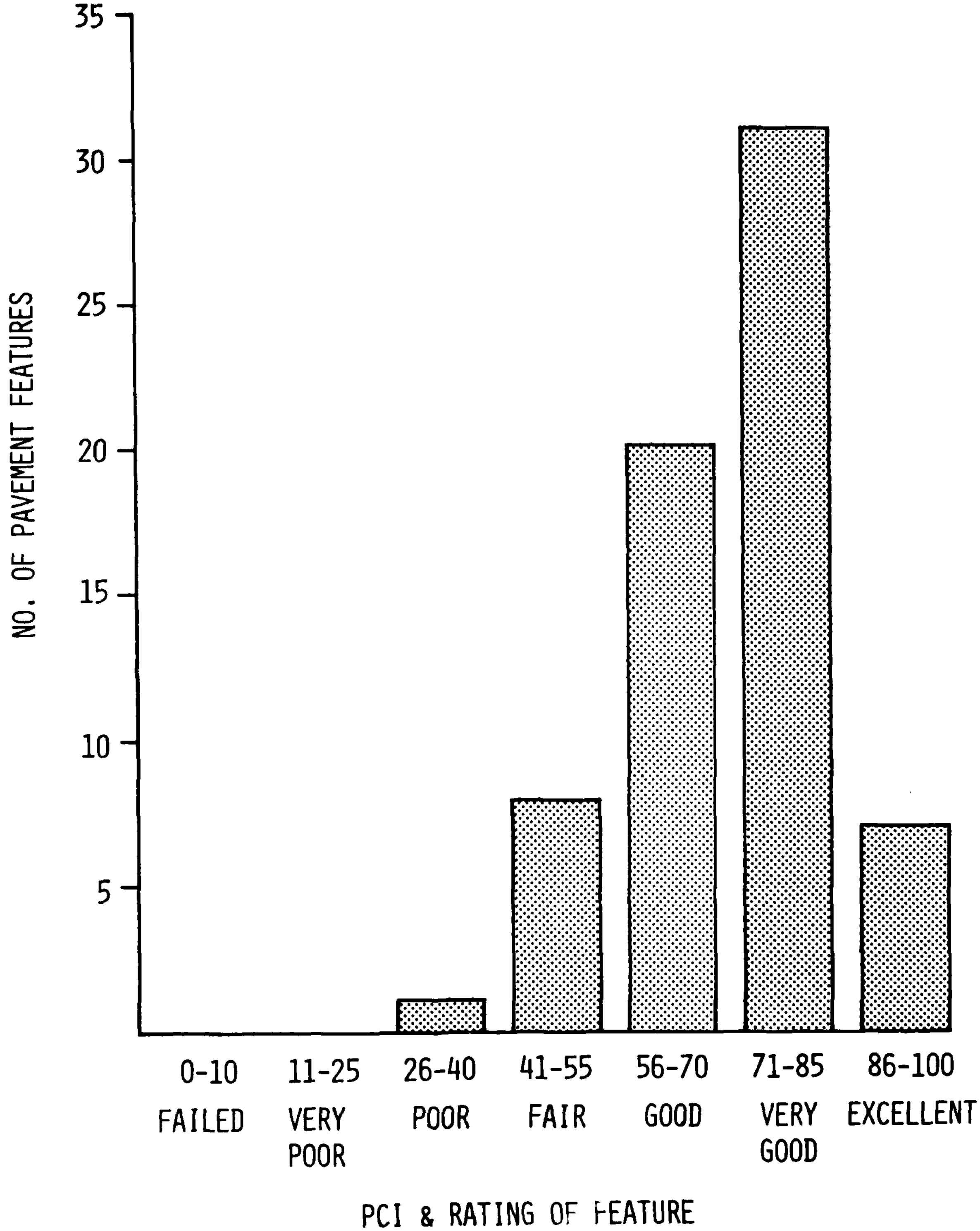


Figure 11. Frequency Distribution of PCIs From Concrete Pavement Features.

Appendix A summarizes all the raw data from each concrete airfield feature.

CONCRETE OVERLAID WITH CONCRETE PAVEMENT DATA

Concrete overlays were surveyed at Langley, Barksdale, and Williams Air Force bases. Table 4 gives the means and ranges of the five features surveyed. The concrete overlays ranged in thickness from 8 to 10 inches, with a mean of 8.6 inches. The mean age of the original slab was 33 years, and the mean age of the overlay was 17 years. The PCI ranged from 60 to 90, with a mean of 75. Appendix A summarizes all the physical data from each airfield feature.

CONCRETE OVERLAID WITH ASPHALT PAVEMENT DATA

Asphalt overlays over original concrete slab airfield pavement features were surveyed at Wright-Patterson, Scott, Williams, Barksdale, Shaw, Hill, Ellsworth, Elmendorf, and Langley Air Force bases. Table 5 summarizes data for the 19 features surveyed. The mean age of the original slab was 29 years, and the mean age of the asphalt overlays was 9.5 years (see Figure 12 for histogram). There are very few relatively older overlays. The mean thickness of the slab was 9.8 inches, and the mean thickness of the asphalt overlay was 2.7 inches (range: 1.5 to 8 inches).

The stress/strength ratio was computed using the same FAA stress charts, but slab thickness was modified to provide for an equivalent thickness that included the asphalt overlay. The following equation was developed, using an elastic layered program:

$$Y = 1.00 + 0.0143\ X \qquad \text{[Equation 1]}$$

where:

Y = stress at bottom of concrete slab with asphalt overlay divided by stress at bottom of a concrete slab with thickness equal to total pavement thickness (asphalt overlay plus concrete slab)

X = percent asphalt thickness of total thickness (asphalt overlay plus concrete slab).

This equation was developed over a range of slab thicknesses (6 to 26 inches) and asphalt overlay thicknesses (0 to 8 inches). For example, assume the following:

Asphalt Overlay = 5 inches

Concrete Slab = 10 inches

Total = 15 inches

$$\text{Percent Asphalt of Total} = \frac{5}{15} \times 100 = 33.3$$

TABLE 4. SUMMARY OF DATA FOR CONCRETE OVERLAY OF CONCRETE AIRFIELD FEATURES (5 TOTAL)

Factor	Mean	Range
PCI	75	60-90
Cracking (Percent Slabs)	24	0-56
Age Original Slab (Years)	33	22-37
Age of Overlay (Years)	17	12-23
Original Slab Thickness (Inches)	10.8	6-19
Overlay Thickness (Inches)	8.6	8-10
Subbase Thickness (Inches)	0	0
Modulus of Rupture (psi) (original slab)	730	700-800
k-value	98	60-130
Freezing Index (Degree Days below 30°F)	0	0
Avg. Annual Rainfall (Inches)	34.8	7-47
Avg. Annual Temp. (°F)	63.0	60-69
Stress/Strength	0.36	0.23-0.52

TABLE 5. SUMMARY OF DATA FOR ASPHALT OVERLAY OF CONCRETE AIRFIELD FEATURES (19 TOTAL)

Factor	Mean	Range
PCI	70.5	48-87
Age of Slab (Years)	28.7	17-37
Age of Asphalt Overlay (Years)	9.5	4-21
Slab Thickness (Inches)	9.8	6-21
Asphalt Overlay Thickness (Inches)	2.7	1.5-8.0
Subbase Thickness (Inches)	6.3	0-30.0
Modulus of Rupture (psi)	711	600-850
k-value (Pounds/cubic inch)	197	60-500
Freezing Index (Degree Days below 32°F)	392	0-2070
Avg. Annual Temp. (°F)	52.8	31-69
Stress/Modulus of Rupture	0.70	0.28-1.61

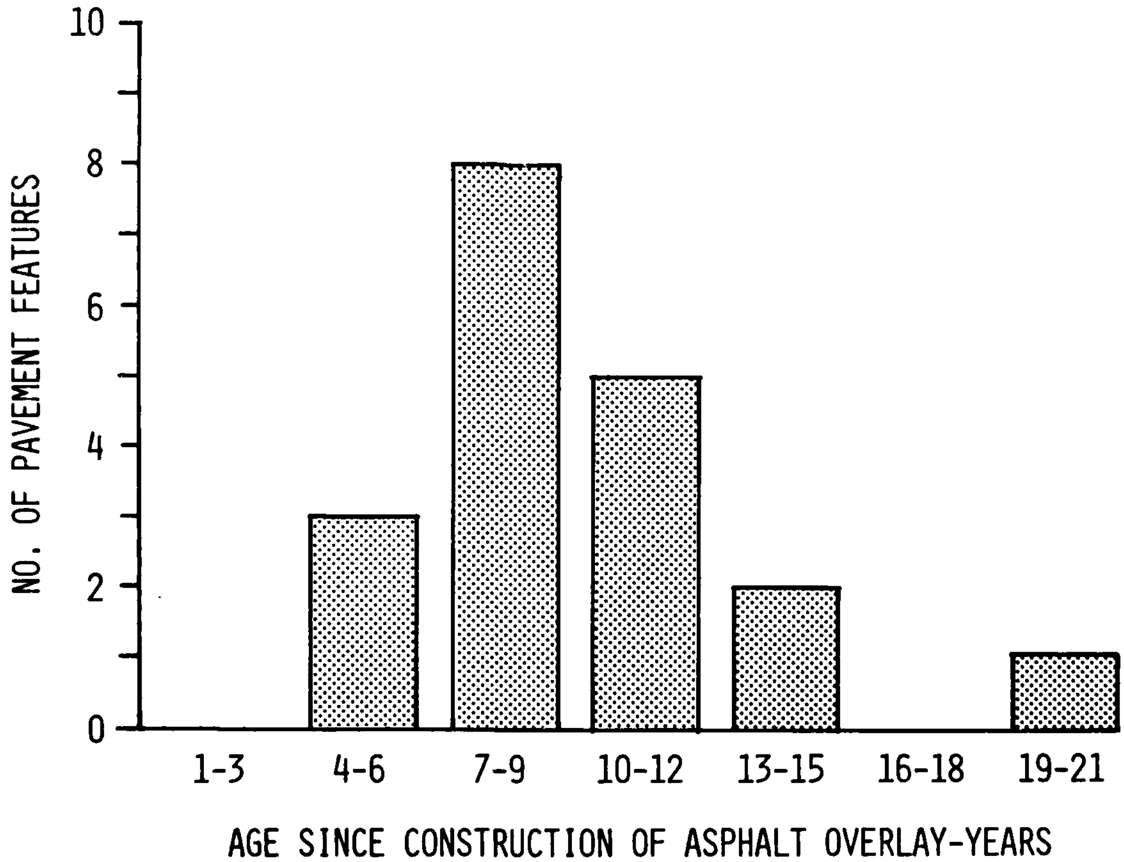


Figure 12. Frequency Distribution of Age of Asphalt Overlay (Concrete Pavement Overlaid With Asphalt).

$$Y = 1.00 + 0.0143 \times 33.3 = 1.476$$

Assume that the stress for a 15-inch slab for a particular aircraft loading is 220 psi, as determined from the FAA charts. Thus, the stress at the bottom of the concrete slab for a 5-inch asphalt overlay over a 10-inch concrete slab is:

$$1.476 \times 220 = 325 \text{ psi}$$

The 325 psi is then divided by the concrete modulus of rupture to determine the stress/strength ratio. The ratio varied from 0.28 to 1.61, with a mean of 0.70.

ASPHALT PAVEMENT DATA (NO OVERLAYS)

Asphalt concrete (AC) pavement data were collected during the PCI development, validation, and training. Reliable information for use in developing the consequence models was obtained for 26 features at Pope, McGuire, Williams, Vance, Homestead, Elmendorf, Ellsworth, Scott, Travis, and Hill airfields. These airfields are located throughout the United States (Figure 5). The following subsections describe the physical characteristics of the pavement features.

Feature Type and Usage

Runways (8 features), taxiways (16 features), and aprons (2 features) were surveyed. Twenty of the features were primary pavements, and six were secondary.

Traffic

Light-, medium-, and heavy-load aircraft currently used in Air Force operations were used at the airfields (Table 6). Most pavement features had a light- and medium-traffic load. The traffic areas were designated as A (5 features), B (12 features), and C (9 features).

AC Thickness

Figure 13 illustrates the distribution of AC thickness, which ranged from 2 to 7.5 inches, with a mean of 3.9 inches.

Base Thickness

Table 7 shows the distribution of base thickness, which ranged from 4 to 27 inches, with a mean thickness of 9.5 inches.

TABLE 6. SUMMARY OF TRAFFIC AT AIRFIELDS*

Airfields	Light Load	Medium Load	Heavy Load
	No. of Pavement features		
Pope	-	4	-
McGuire	-	2	-
Williams	3	-	-
Vance	7	-	-
Homestead	3	-	-
Elmendorf	-	1	-
Ellsworth	-	-	2
Scott	-	2	-
Travis	-	1	-
Hill	1	-	-
Total	14	10	2

* For indication of aircraft type, see Table 1.

TABLE 7. FEATURE BASE THICKNESS

Base (Inches)	No. Features
4	1
6	11
8	1
9	1
10	1
11	2
12	4
13	4
27	1

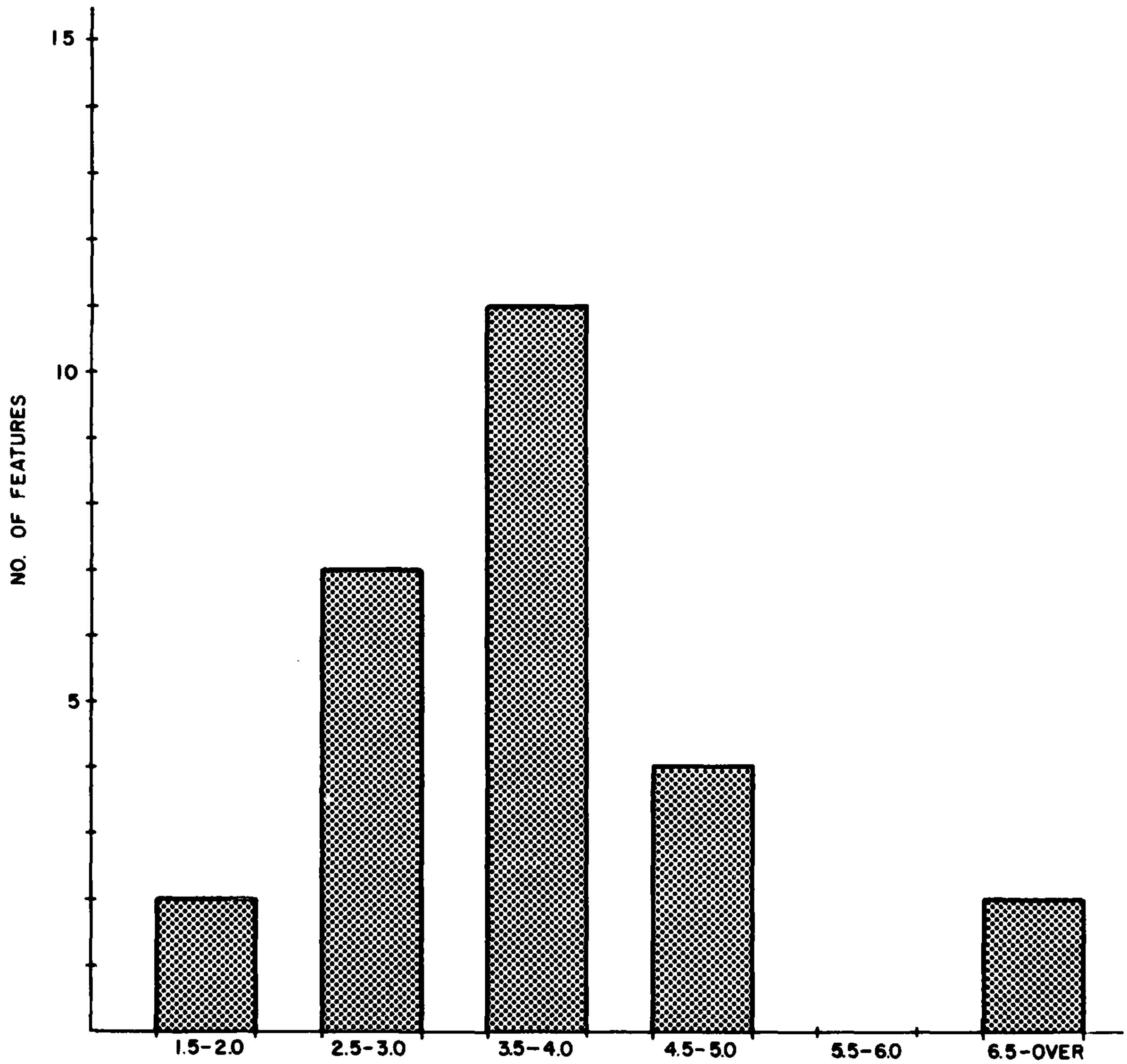


Figure 13. Frequency Distribution of AC Thickness (AC Pavement -- No Overlay).

Subbase Thickness

Table 8 shows the distribution of subbase thickness, which ranged from 0 to 28 inches, with a mean thickness of 9.4 inches.

Base California Bearing Ratio (CBR)

The base material included silty sand, crushed limestone, and cement-stabilized soil. Figure 14 illustrates the distribution of the base CBR. A range of 24 to 100 with a mean CBR of 71 percent was obtained.

Subbase CBR

The subbase material included coarse sand, silty sand, and clay sand. Table 9 shows the distribution of the subbase CBR. A range of 0 to 100 was obtained, with a mean CBR of 24.7 percent.

Subgrade CBR

Table 10 shows the distribution of subgrade CBR. A range of 4 to 80, with a mean CBR of 21.8 percent was obtained.

Age of Construction

The age of the pavement from time of construction to the date of the condition survey ranged from 0.5 to 35 years, with a mean of 18 years. Figure 15 illustrates the distribution of pavement age.

Maintenance

The only maintenance activity included was patching, which was expressed as a percent area of the pavement feature. The percent patching ranged from 0 to 0.5, with a mean of 0.135.

Climate

Climate was characterized by the freezing index, average annual precipitation, average annual temperature, annual temperature range, and daily temperature range. The ranges and means of these variables are as follows:

	Range	Mean
Freezing Index (degree days below 32°F)	0 - 2070	175
Precipitation (inches)	7 - 56	31.7
Average Annual Temperature (°F)	36 - 69	59.7
Average Annual Temperature Range (°F)	15 - 51	40.0
Average Daily Temperature Range (°F)	15 - 31	21.7

TABLE 8. FEATURE SUBBASE THICKNESS

Base Inches	No. Features	Base Inches	No. Features
0	8	11	2
5	1	16	1
7	4	18	2
8	2	24	2
9	2	28	2

TABLE 9. FEATURE SUBBASE CBR

CBR (%)	No. Features
0 - 10	8
11 - 20	6
21 - 30	4
31 - 40	4
41 - 50	2
51 - 60	0
61 - 70	0
71 - 80	1
81 - 90	0
91 - 100	1

TABLE 10. FEATURE SUBGRADE CBR

CBR (%)	No. Features
0 - 10	16
11 - 20	1
21 - 30	3
31 - 40	2
41 - 50	1
51 - 60	0
61 - 70	0
71 - 80	3

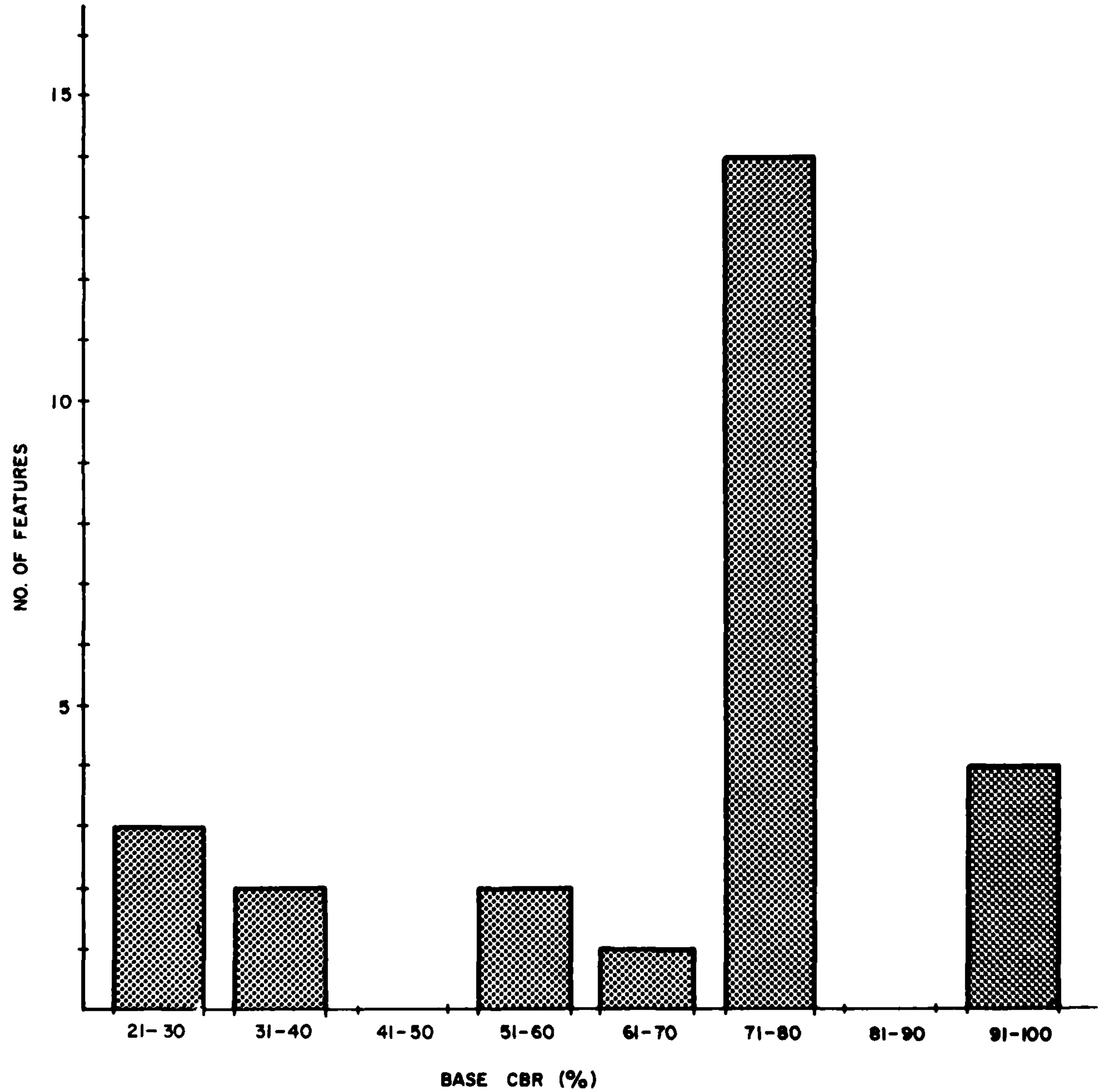


Figure 14. Frequency Distribution of Base CBR of Features (AC Pavement -- No Overlay).

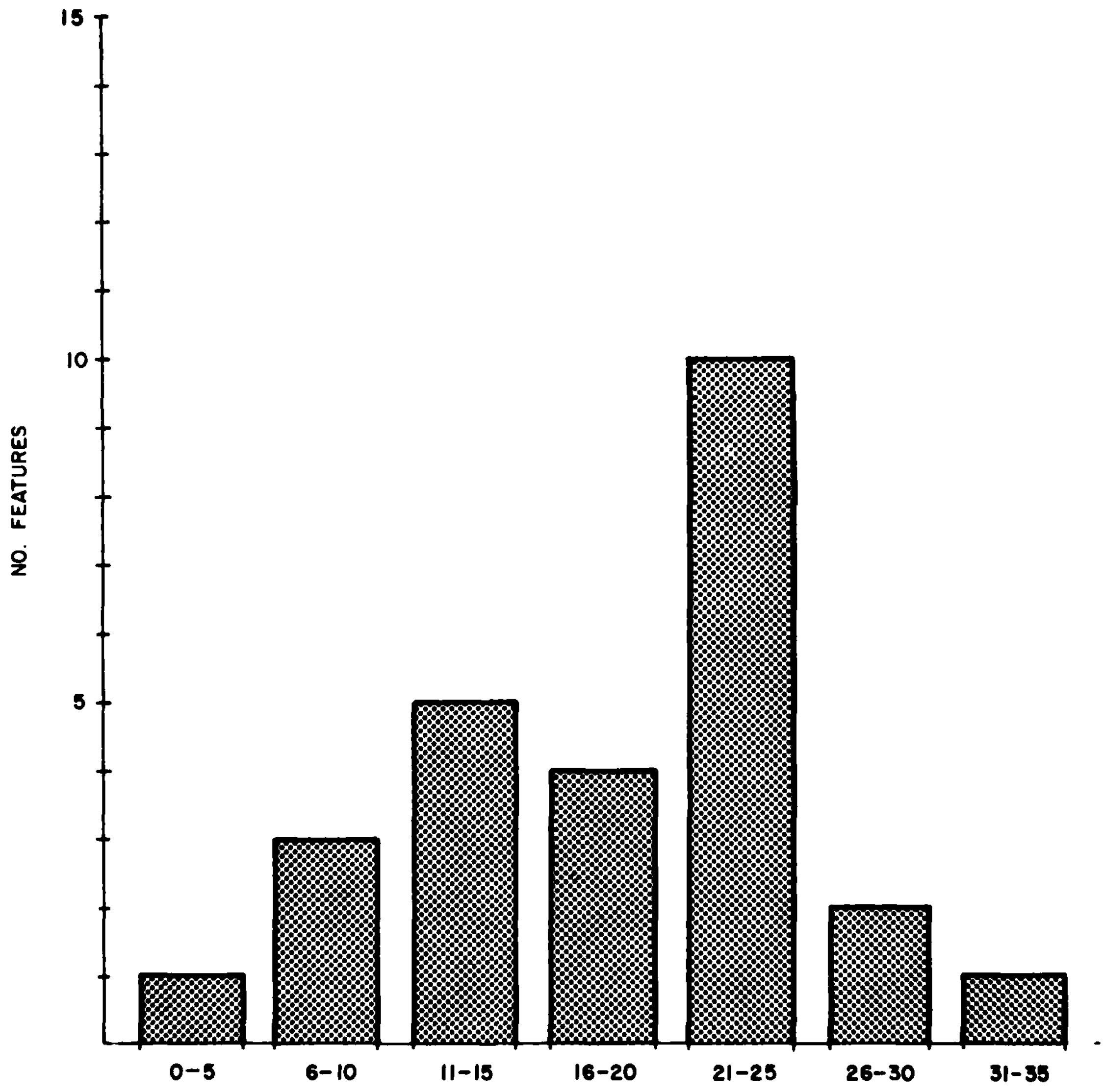


Figure 15. Frequency Distribution of Pavement Age (Years) (AC Pavement -- No Overlay).

The load repetition factor (α), was introduced by Brown and Rice (Reference 8) as a thickness percentage to account for the number of traffic passes in flexible pavement design. The design equation they have developed is as follows:

$$t = \alpha\{\sqrt{A}[0.048 - 1.1562 \cdot (\text{Log}\ \frac{CBR}{pe}) - 0.06414(\text{Log}\ \frac{CBR}{pe})^2 - 0.473\ (\text{Log}\ \frac{CBR}{pe})^3]\} \qquad \text{[Equation 2]}$$

where: t = Pavement thickness above layer considered (inches)
A = Contact area of one tire (square inches)
CBR = California Bearing Ratio for layer considered
pe = Tire pressure (psi) calculated using contact area A, and equivalent single-wheel load (ESWL) P_e determined at depth t;pe = P_e/A.

To use Equation 2, the ESWL (P_e) at any selected depth, t, must be computed first. P_e can be determined from the following equation (Reference 9), which is based on the Boussinesq one-layer theory and the Corps of Engineers equal deflection approach:

$$P_e = \frac{P_k \sum_{i=1}^{n} F_{imax}}{F_e} \qquad \text{[Equation 3]}$$

where: P_k = wheel load per individual wheel
F_e = deflection factor under the centerline of the equivalent single-wheel at depth t.

$$F_e = \frac{1.5}{[1 + (t/a)^2]^{\frac{1}{2}}} \qquad \text{[Equation 4]}$$

(F_e can also be determined from Figure 16)

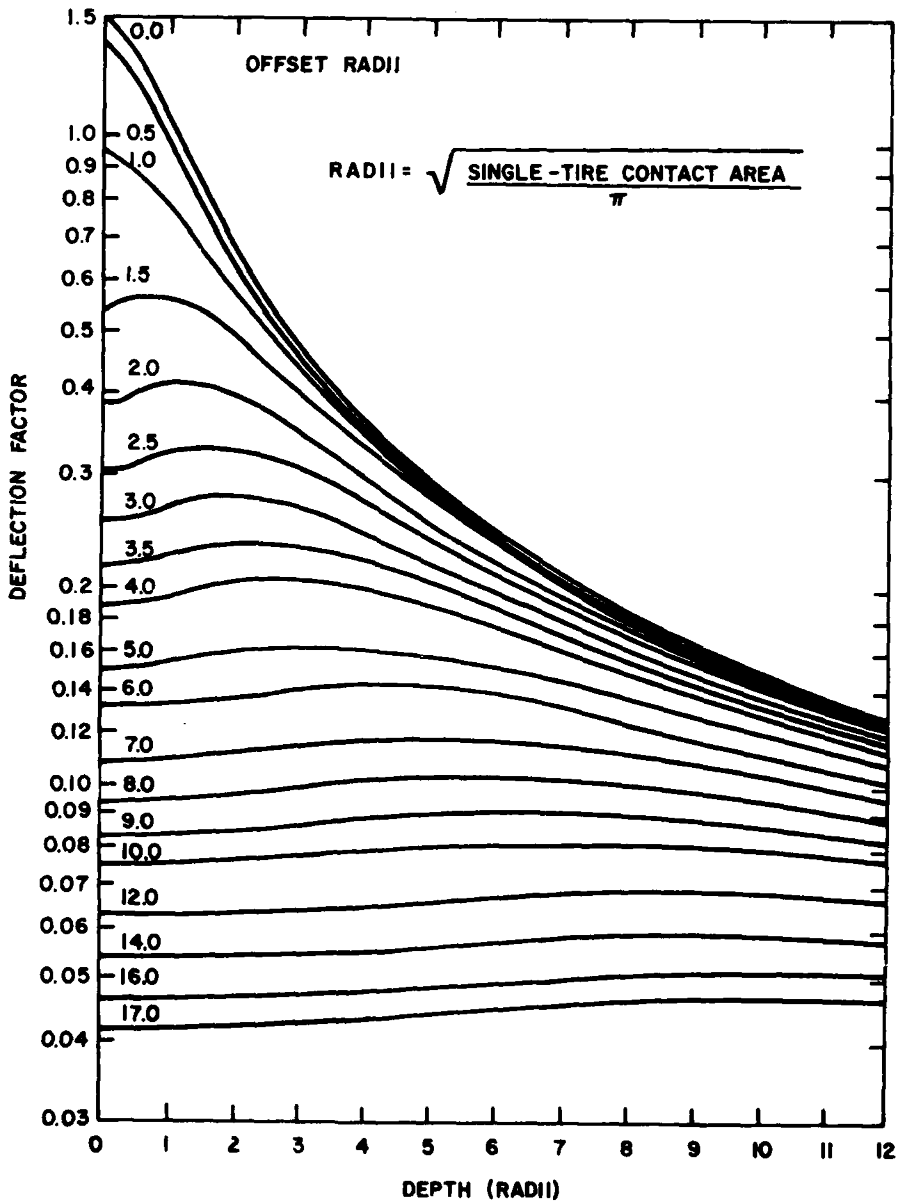


Figure 16. One-Layer Deflection Factor Curves.

a = radius of contact of tire of equivalent single wheel
= radius of contact of one tire of group of wheels being considered.

ΣF_{imax} = maximum sum of deflection factors F_i at depth t caused by wheels (i=1 to n) being considered; the F_i values are determined from Figure 16.

Several computations should be made to determine F_{imax}. For dual wheels, ΣF_i values are usually computed under one wheel and the center of the two wheels, and the maximum value is then selected. Figure 17 illustrates the determination of P_e for a C-130 aircraft at depth of 20 inches.

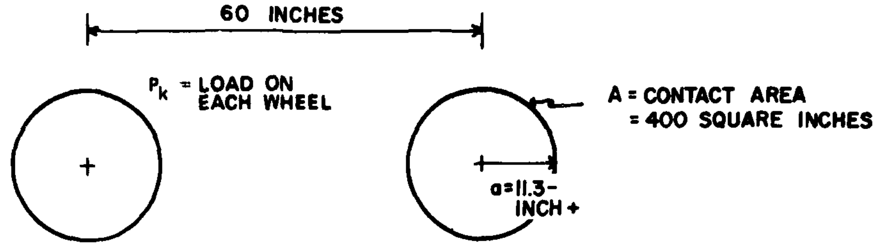
Computation of ESWL may be expedited by using Figures 18 and 19. For example, for the C-130 aircraft at a depth of 20 inches, the ESWL is determined from Figure 17 to be 60 percent of load on a controlling number of wheels. The controlling number of wheels for the C-130 aircraft is two (or one main gear), as indicated in Table 11. The ESWL is the same as that obtained in Figure 17.

The load repetition factor for all pavement features was determined at the AC/base interface (α_{AC}) and at the subgrade level (α_{SG}). The thickness t, used to compute α_{SG}, does not consider the difference in materials (i.e., AC, granular material, etc.) Therefore, equivalency factors (Table 12) for different materials were used to compute an equivalent total thickness above the subgrade. The load repetition factor at the subgrade level, which was also calculated using the computed equivalent thickness, was included in the analysis. The mean and range of the load repetition factors for all pavement features are:

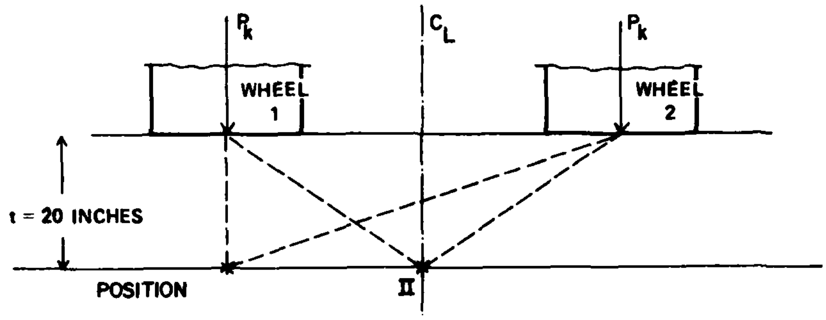
	Mean	Range
Load repetition factor at AC/base interface	0.70	0.34 - 1.30
Load repetition factor at subgrade level	1.48	0.72 - 2.83
Load repetition factor at subgrade level based on equivalent thickness	1.89	0.818 - 3.06

Pavement Condition Index (PCI)

The PCI was determined for each feature according to the procedures described in AFCEC TR 44 (Reference 5). With the exception of a few cases, a statistically acceptable number of sample units was used to determine the PCI of the features. (After more data become available, it is recommended that these few cases be removed.) Figure 20 shows the distribution of the PCI. The PCI values ranged from 12 to 100, with a mean of 61.



PLAN VIEW OF ONE MAIN GEAR OF C-130 AIRCRAFT



Position I

$$\left.\begin{array}{l}\text{Wheel \#1: Depth (radii)} = \dfrac{20}{11.3} = 1.77 \\ \text{Offset (radii)} = \dfrac{0}{11.3} = 0\end{array}\right\} \begin{array}{l}\text{From Figure 16} \\ F_1 = 0.73\end{array}$$

$$\left.\begin{array}{l}\text{Wheel \#2: Depth (radii)} = \dfrac{20}{11.3} = 1.77 \\ \text{Offset (radii)} = \dfrac{60}{11.3} = 5.3\end{array}\right\} \begin{array}{l}\text{From Figure 16} \\ F_2 = .15\end{array}$$

$$\therefore\ \Sigma F_i = F_1 + F_2 = .73 + .15 = 0.88$$

Position II

Similarly $F_1 = F_2 = 0.31$, $\Sigma F_i = 0.62$

$$\therefore\ \Sigma F_{i_{max}} = \Sigma F_i \text{ @ position I} = 0.88$$

Fe equals F_1 in position I = 0.73

$$P_e = P_k \frac{\Sigma F_{i_{max}}}{Fe} = P_k \frac{0.88}{0.73}$$

$\boxed{\therefore\ P_e = 1.2\ P_k}$ i.e.:

The ESWL = 1.2 of load on single wheel

= 0.6 of load on one main gear

Figure 17. Example Computation of ESWL for a C-130 Aircraft.

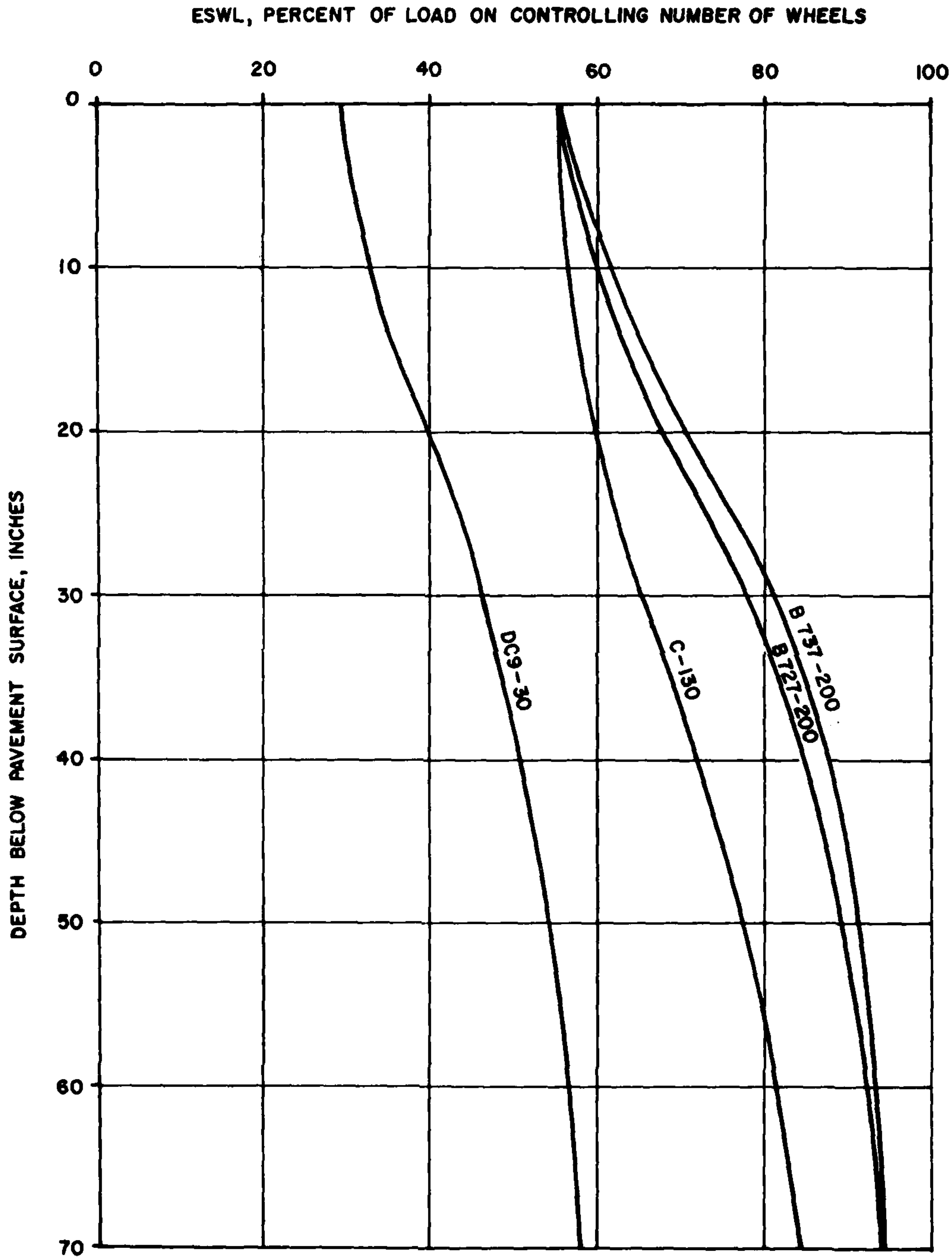


Figure 18. ESWL as a Function of Aircraft Type and Depth Below Pavement Surface.

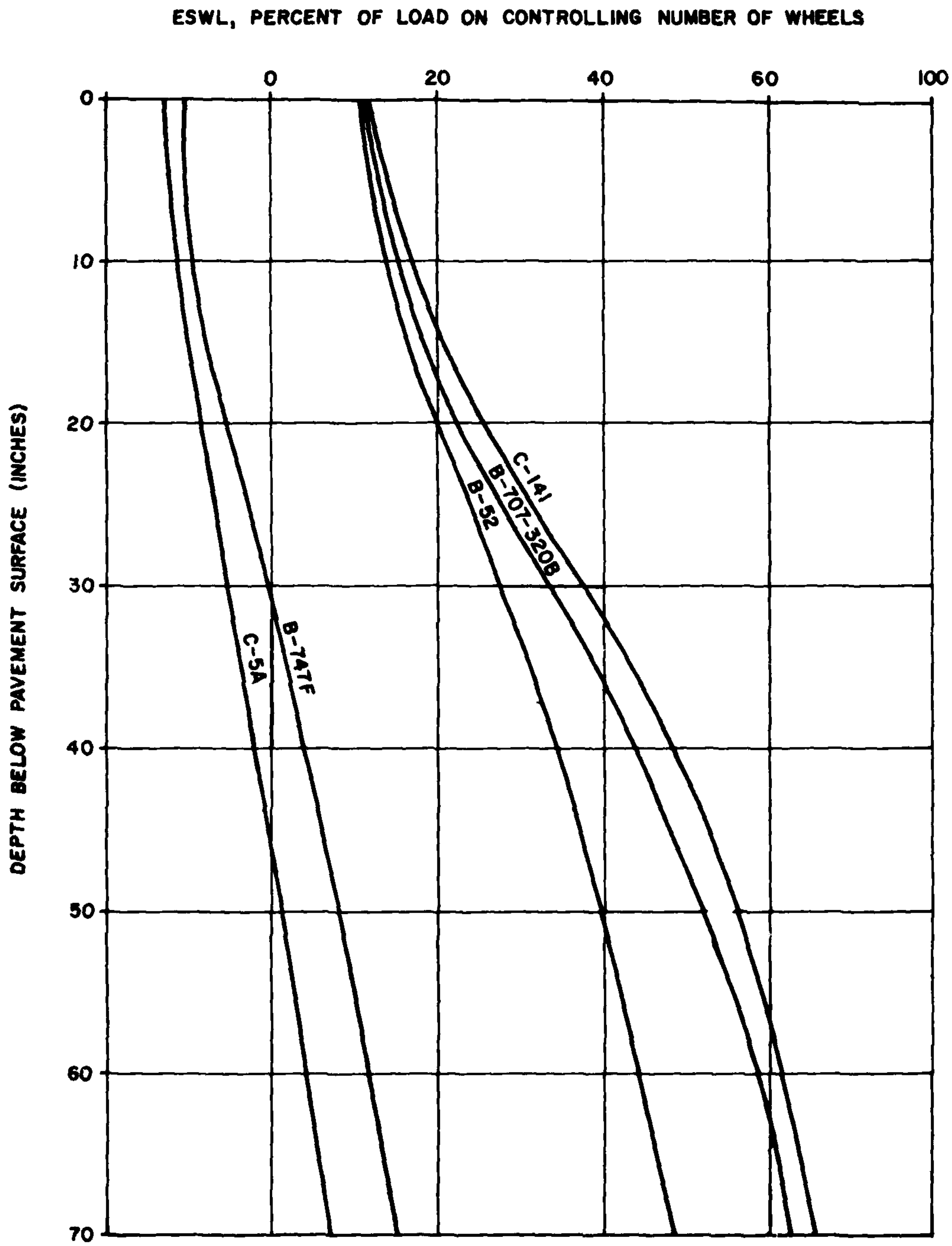


Figure 19. ESWL as Function of Aircraft Type and Depth Below Pavement Surface.

TABLE 11. AIRCRAFT TIRE CONTACT AREAS AND TOTAL NUMBER OF MAIN GEAR WHEELS

Aircraft	Tire Contact Area (Square Inches)	Total No. of All Main Gear Wheels (Hm)	No. of Controlling Wheels (Nc)	Pass to Coverage Ratio: Taxiways and Runway Ends	Pass to Coverage Ratio: Runway Interior
C-123	100	2	1	5.23	10.38
F-4	100	2	1	8.58	17.00
F-111	241	2	1	4.92	9.80
C-130	400	4	2	2.09	4.05
DC-9-30	165	4	4	3.58	6.90
737-200	174	4	2	3.62	6.73
727-200	237	4	2	3.25	6.00
707-320B	218	8	4	1.62	3.00
C-141	208	8	4	1.72	3.17
C-5	285	24	24	0.81	1.10
747F	245	16	16	1.85	2.77
B52	267	8	4	1.63	2.00

TABLE 12. EQUIVALENCY FACTORS

Material	Stabilizing Agent	Surface Course	Base Course	Subbase Course	Subgrade
AC	Asphalt	1.70	1.70	1.70	--
Unbound Crushed Stone	--	--	1.40	1.40	--
Sand-Gravel	Cement	--	1.60*	1.60**	--
Clay-Gravel	Cement	--	1.45*	1.45**	--
Fine-Grained Soil	Cement	--	1.25*	1.25**	--
Clay-Sand	Cement	--	1.15*	1.15**	--
Clay-Sand	Fly Ash	--	--	1.15**	--
Sand-Gravel or Clay-Gravel+	Asphalt	--	1.50	1.50	--
Fine-Grained Soil	Lime	--	--	1.10++	1.10+++
Unbound Granular Material	--	--	--	1.00	--

* To use equivalency factor in evaluation, unconfined compressive strength of layer must be 1000 psi.

** To use equivalency factor in evaluation, unconfined compressive strength of layer must be 700 psi.

\+ Bituminous.

++ To use equivalency factor in evaluation, unconfined compressive strength of layer must be 2000 psi.

+++ To use equivalency factor in evaluation, unconfined compressive strength of layer must be 100 psi.

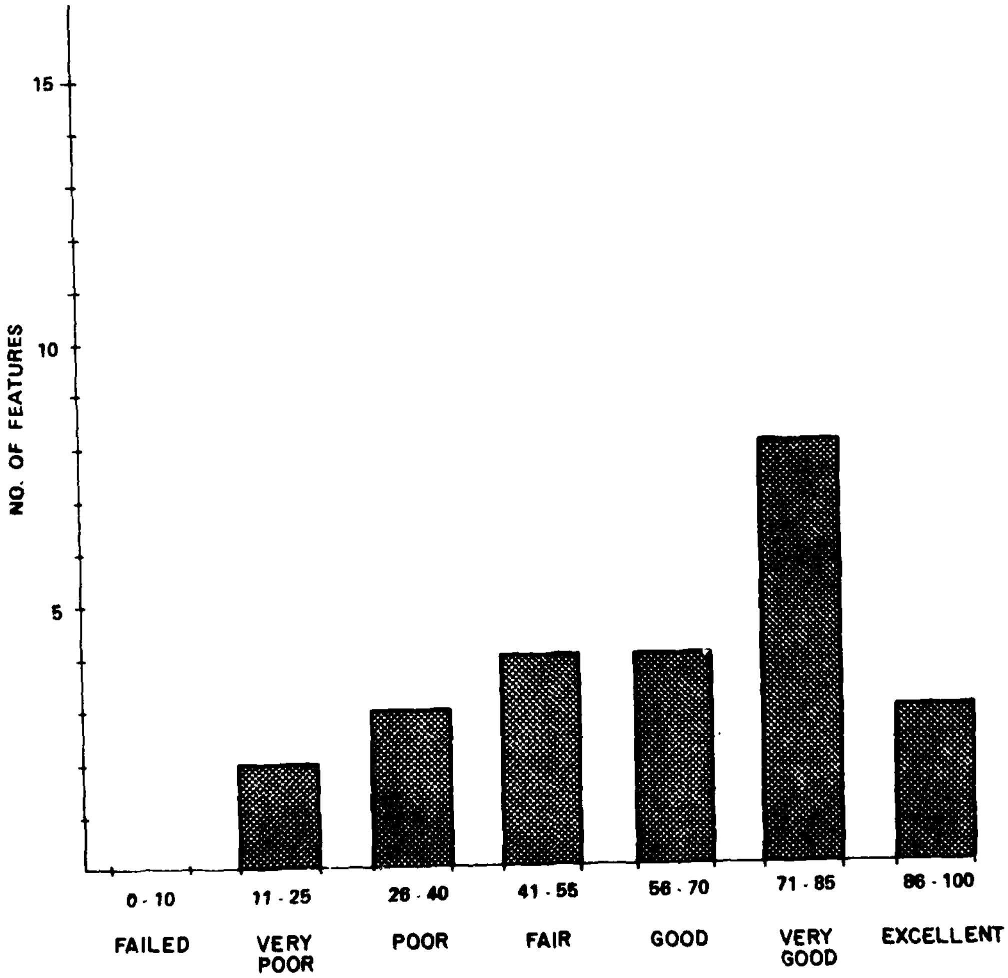


Figure 20. Frequency Distribution of PCI for Asphalt Pavement Features (No Overlay).

Alligator Cracking

The percentage of area containing low-, medium-, and high-severity alligator cracking was computed for each feature from collected distress data. Table 13 shows the distribution of percent of alligator cracking. The percentage of total alligator cracking (i.e., low plus medium plus high severity) ranged from 0 to 51, with a mean of 6.4 percent. Half of the features had a total percentage of alligator cracking that was less than 1 percent. Table B-1 of Appendix B summarizes all the data from each feature.

ASPHALT PAVEMENT OVERLAID WITH AC DATA

AC overlays over flexible pavements were surveyed at Pope, George, McGuire, Eielson, Ellsworth, Scott, and Hill Air Force bases. Eleven features were surveyed; Table 14 gives the means and ranges of the individual characteristics. Table B-2 of Appendix B summarizes all of the data from each feature.

TABLE 13. SUMMARY OF THE ALLIGATOR CRACKING OF ASPHALT PAVEMENT FEATURE

	Mean	Range
Low Alligator Cracking	1.68	0 - 10.2
Medium Alligator Cracking	4.8	0 - 43.6
High Alligator Cracking	0.3	0 - 6.9
Total Alligator Cracking	6.8	0 - 50.8

TABLE 14. SUMMARY OF DATA FOR AC OVERLAY OF FLEXIBLE PAVEMENT

Factor	Mean	Range
PCI	56.8	17 - 89
Alligator Cracking (Percent)	5.6	0.09 - 26.5
Patching (Percent)	0.85	0 - 4.7
Age of Original Construction (Years)	28	19 - 35
Age of Overlay (Years)	9.4	4 - 23
Original Thickness of AC (Inches)	4.2	2.5 - 6.5
Thickness of AC Overlay (Inches)	2.4	0.5 - 3.0
Base Thickness (Inches)	8.0	4 - 16.5
Subbase Thickness (Inches)	8.2	0 - 42
Base CBR (Percent)	56	24 - 100
Subbase CBR (Percent)	26	0 - 100
Subgrade CBR (Percent)	20	5 - 50
Freezing Index (Degree Days below $32^{o}F$)	1095	0 - 5320
Precipitation (Inches)	29.6	3.5 - 47
Average Annual Temperature (^{o}F)	50.8	26 - 61
Average Annual Temperature Range (^{o}F)	22	19 - 29
Average Daily Temperature Range (^{o}F)	46	35 - 61
Load Repetition Factor at AC/Base Interface	.83	0.43 - 1.43
Load Repetition Factor at Subgrade Level	1.25	0.59 - 3.0
Load Repetition Factor at Subgrade Level Based on Equivalent Thickness	1.50	0.73 - 3.42

SECTION III

CONCRETE PAVEMENT PCI AND CRACKING PREDICTION

OBJECTIVES OF THE PREDICTION MODELS

The principal objectives of the prediction model are to forecast the PCI and key distresses of an existing pavement feature to predict the "consequences" of a variety of possible M&R alternative actions. Such capability would aid greatly in deciding what M&R alternative to recommend for specific pavement features. Ideally, the models should be capable of forecasting PCI and key distresses for the following actions: application of routine M&R, application of major M&R, placement of an overlay, and proposal of an aircraft mission change. The models should also provide insight into the variables that cause deterioration of concrete pavements.

These objectives were all addressed, but only partially achieved because of an insufficient data base. However, the results indicate that these objectives can be achieved if an adequate data base is obtained (i.e., many additional airfield pavement features). Thus, the models discussed in this section should be considered as tentative, not as final validated models. Nevertheless, they illustrate that with an adequate data base, there is great potential to develop predictive models that are very practical and useful for helping make pavement maintenance and operational decisions.

DEVELOPMENT OF PCI PREDICTION MODELS

Nearly all of the concrete airfield pavements constructed on U.S. Air Force bases have been plain-jointed concrete with short joint spacings (12 to 25 feet). Some of these pavements have been overlaid with either asphalt or concrete because of either a change in the mission aircraft or significant deterioration.

The first step in model development was to identify all major variables (called independent variables) believed to significantly influence the PCI. This was accomplished by reviewing literature, interviewing major command and base pavement engineers, and reviewing previous experience of the project staff. The availability of information, cost, and time required to collect each independent variable for each airfield feature was assessed, and it was concluded that several variables could not be obtained within the available resources. Table 15 lists the independent variables considered important in the development of the concrete pavement PCI prediction models and those from which data were actually collected. The chosen data were collected from 67 concrete features having no overlay, 19 asphalt overlay features, and 5 concrete overlay features having the characteristics described in Section II.

After the initial data collection, considerable effort was required to "clean" the data and eliminate errors. The data were coded and keypunched for processing. The Statistical Package for the Social Sciences (SPSS)

TABLE 15. LIST OF INDEPENDENT VARIABLES CONSIDERED IN THE DEVELOPMENT OF THE CONCRETE PAVEMENT PCI PREDICTION MODELS

I. Variables used to develop models (data obtained from each feature):

AGE (Time Since Original Construction of Slab) -- Years
SLAB (Concrete Slab Thickness) -- Inches
BASE (Granular Subbase Thickness) -- Inches
JSL (Longest Joint Spacing) -- Feet
JSS (Shortest Joint Spacing) -- Feet
MR (Modulus of Rupture of Concrete) -- psi
K (k-Value of Slab Foundation) -- Pounds/Cubic Inch
ACWGT (Gross Maximum Weight of Critical Aircraft Using Feature) -- kips
FAT (Ratio of Stress to Modulus of Rupture [Strength] x 100)
PEI (Pavement Evaluation Index)
FEAT (Type of Feature: Runway, Taxiway, Apron)
AREA (Traffic Area: A, B, C)
PS (Usage of Feature: Primary or Secondary)
FI (Freezing Index) -- Degree Days Below 32^{o}F
PPT (Average Annual Precipitation) -- Inches
TEMP (Average Annual Temperature) -- ^{o}F
SR (Slab Replacement) -- Percent of Total Slabs
PATCH (Large Patching) -- Percent of Total Slabs
ACOL (Existence of AC Overlay)
PCOL (Existence of Concrete Overlay)

II. Other variables considered which had important effects on PCI data, but were not obtained because of cost, time required, or lack of availability:

Number of Aircraft Passes Over Feature
Joint Design
Joint Load Transfer Efficiency
Several Additional Climatic Variables (Number of Freeze-Thaw Temperature Gradients Through Slab, Monthly Distribution of Precipitation, etc.)
Drainage Condition of Pavement Feature

(Reference 10) was used for all data analysis. The SPSS is an excellent, well-documented, and widely used system useful for all types of statistical analyses.

The data were first analyzed by obtaining frequency plots, cross tabulation tables, and graphs of each independent variable (i.e., AGE, FI, FAT) vs the dependent variable (PCI). Figures 21 through 27 are graphs of variables having the highest correlations. Table 16 is a matrix which shows how each variable correlates independently with the others. The matrix shows considerable intercorrelation between the variables, which complicates the development and interpretation of a predictive model.

A tentative linear model was selected and many runs of the SPSS stepwise regression program were conducted to obtain the best predictive model of PCI as a function of the independent variables listed in Table 15. The model was constrained so that it would fit the important boundary condition of the PCI = 100 just after initial construction, or overlay. This boundary condition would occur since there would normally be no observable distress just after construction.

Many runs of the SPSS stepwise regression program were made over a period of several months. Table 17 gives the final results. The stepwise regression procedure starts with the simple correlation matrix between the PCI and each variable and enters into regression the independent variable most highly correlated with the dependent variable (PCI) (Step 1). Using partial correlation coefficients, it then selects the next variable to enter regression, i.e., that variable whose partial correlation with PCI is highest. At every step, the procedure re-examines the variables included in the equation in previous steps (Reference 10). The program does this by testing every variable at each stage as if it had been the last to enter and checks its contribution by means of the partial F-test.* Thus, some variables may be removed from the equation after they have been entered.

The more independent variables there are entering the equation, the better the equation will fit or model the data for predicting PCI. However, after a certain point, the effect of additional variables in terms of increasing the R^2 or decreasing the standard error will be insignificant. One criterion often used as a basis for deciding how many steps (or variables) to retain in a regression model is inclusion of only those variables whose estimated coefficients are significant at the 0.05 level. The equation would therefore include variables entered in Steps 1 through 8, yielding the predictive equation on page 52.

* Standard statistical test.

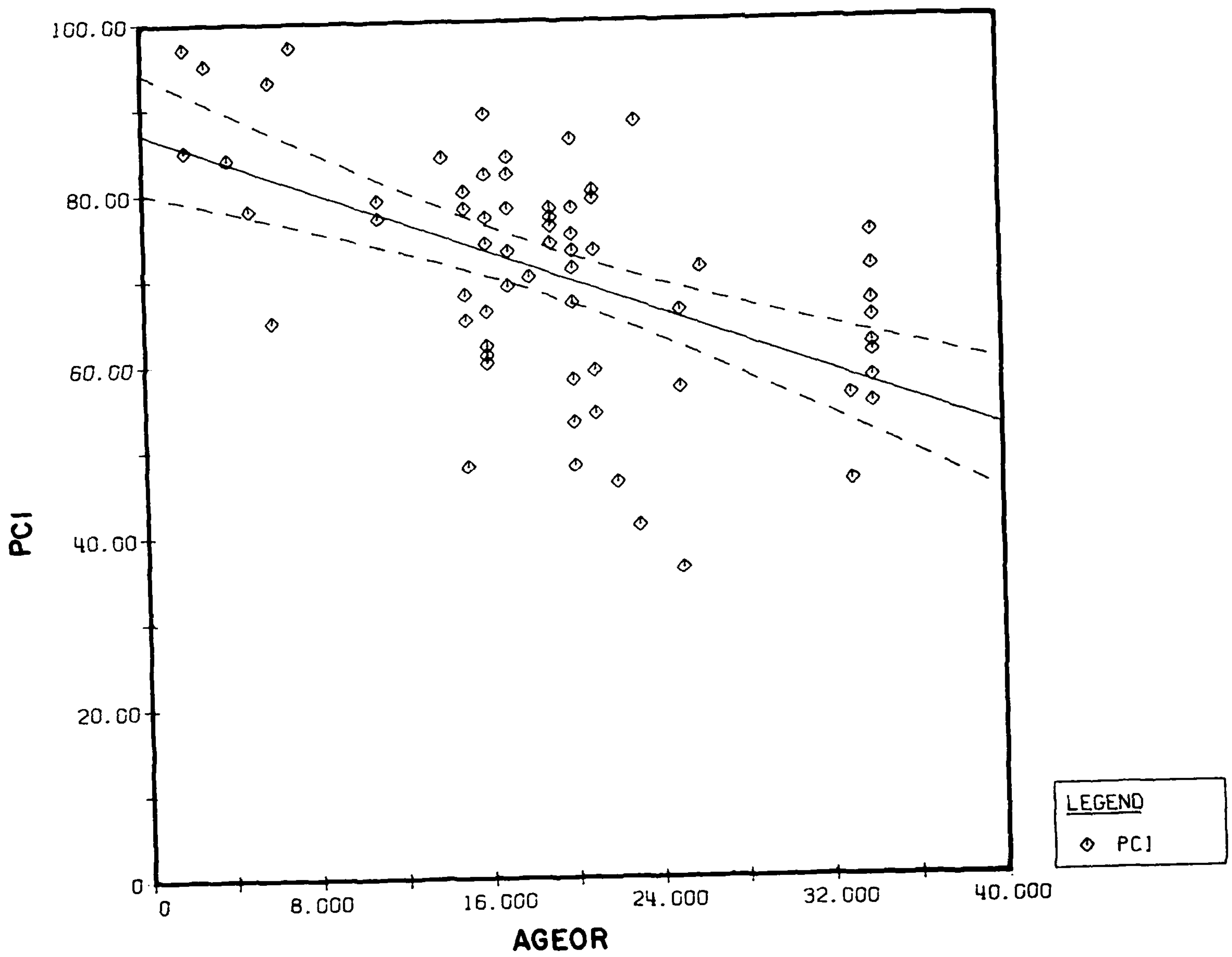


Figure 21. PCI Versus Time Since Construction (AGE) for Concrete Features With and Without Asphalt Overlay.

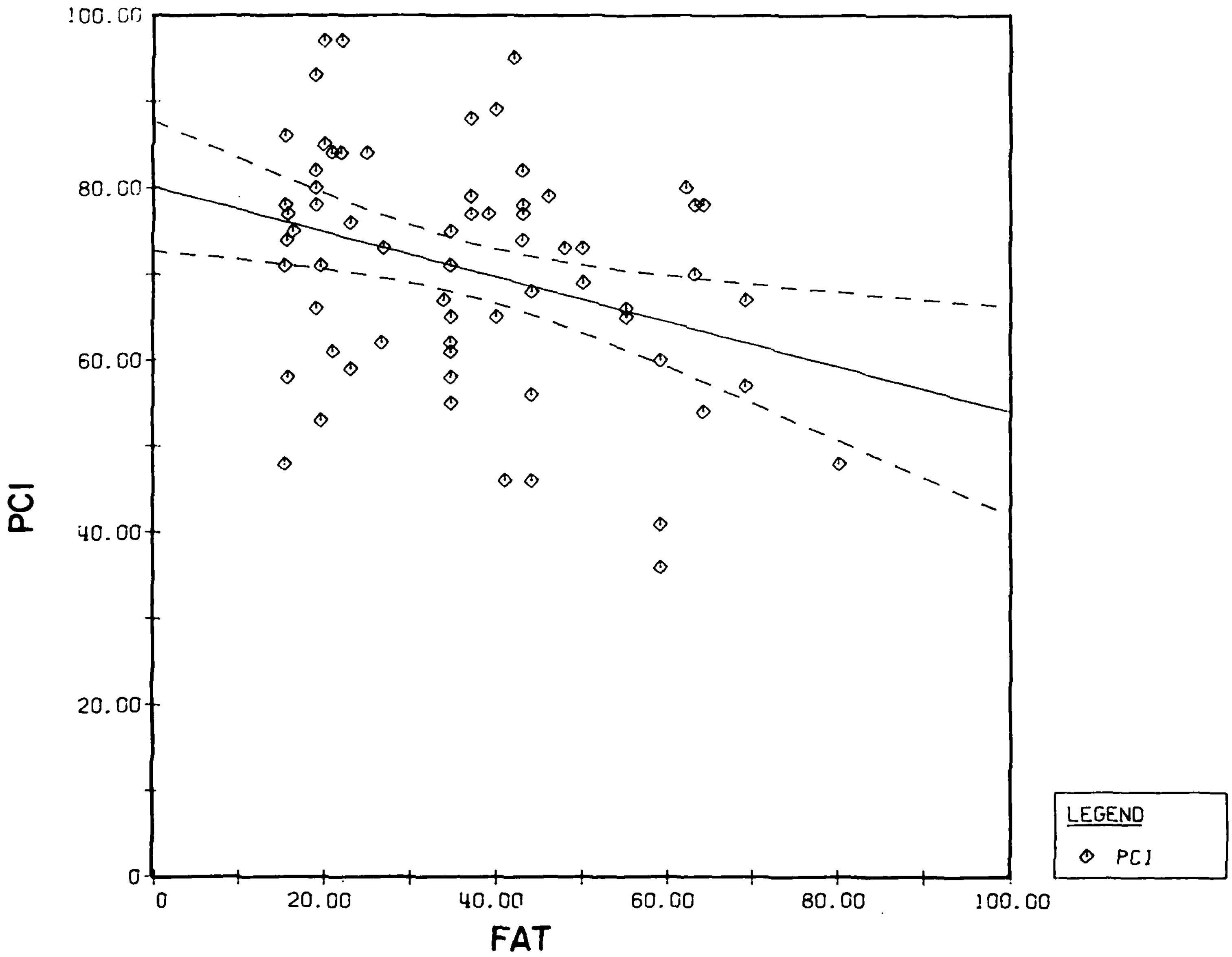


Figure 22. PCI Versus FAT for Plain-Jointed Concrete Airfield Pavement Features With and Without Asphhalt Overlay.

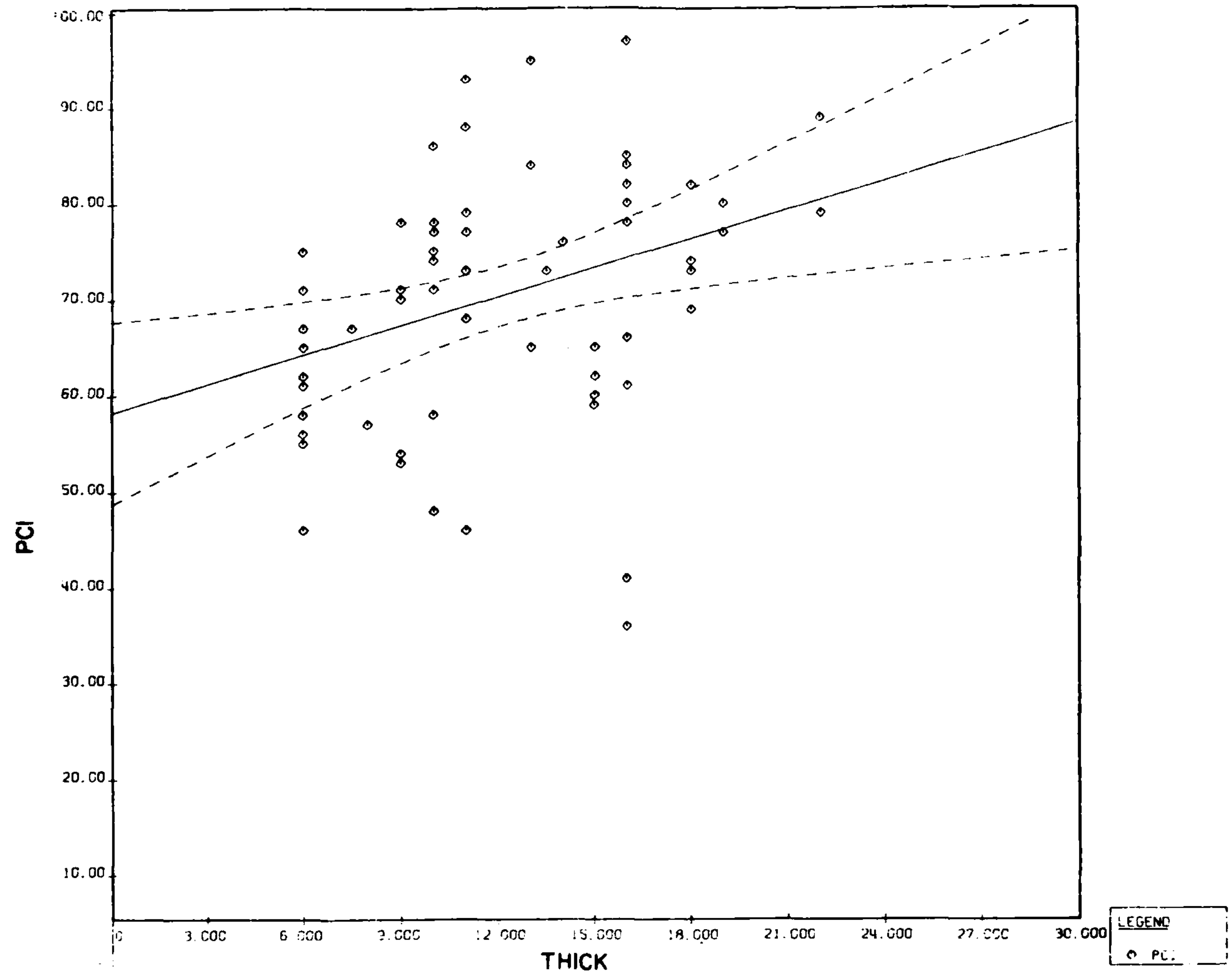


Figure 23. PCI Versus Concrete Slab Thickness for Plain-Jointed Concrete Airfield Pavemant Features With and Without Asphalt Overlay.

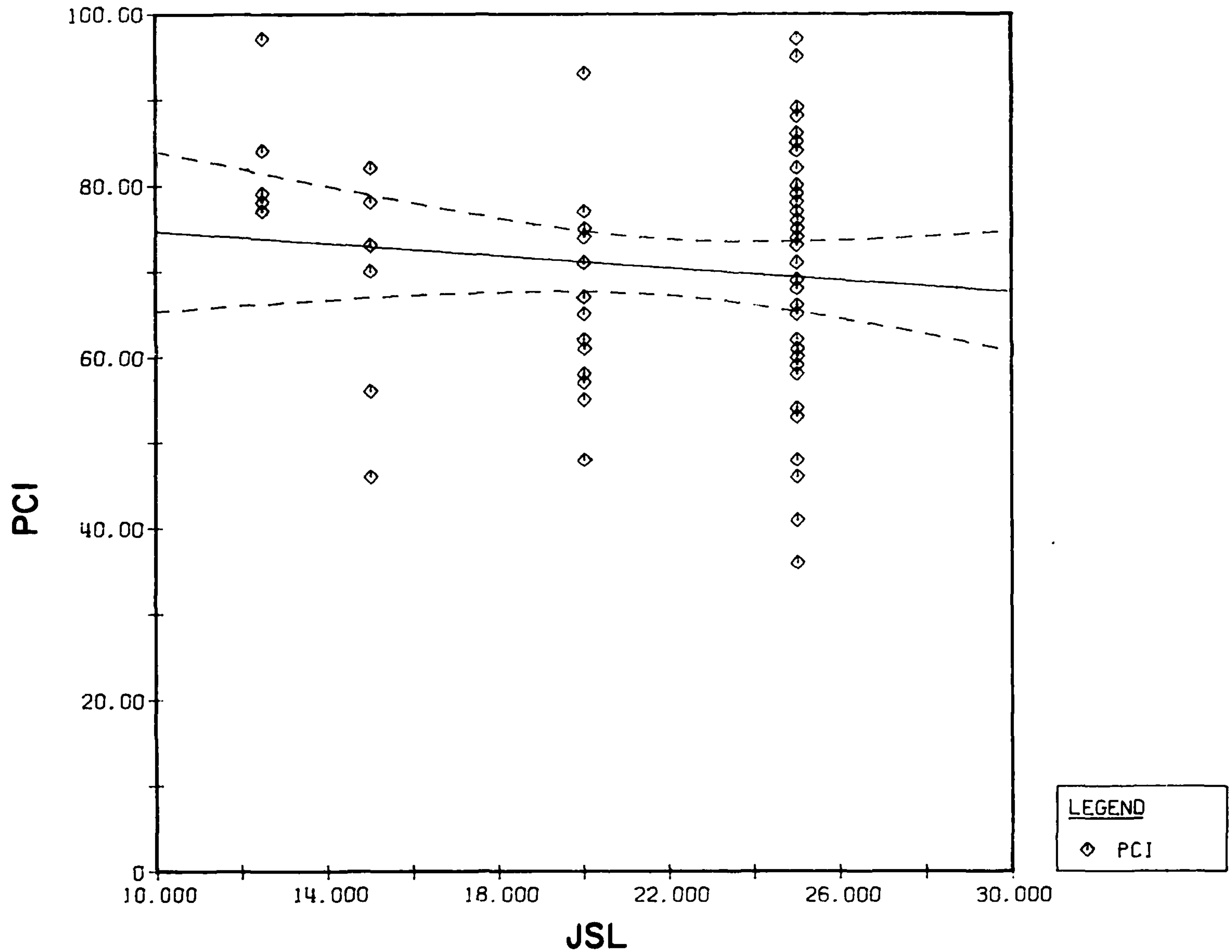


Figure 24. PCI Versus Joint Spacing for Plain-Jointed Concrete Airfield Pavement Features With and Without Asphalt Overlay.

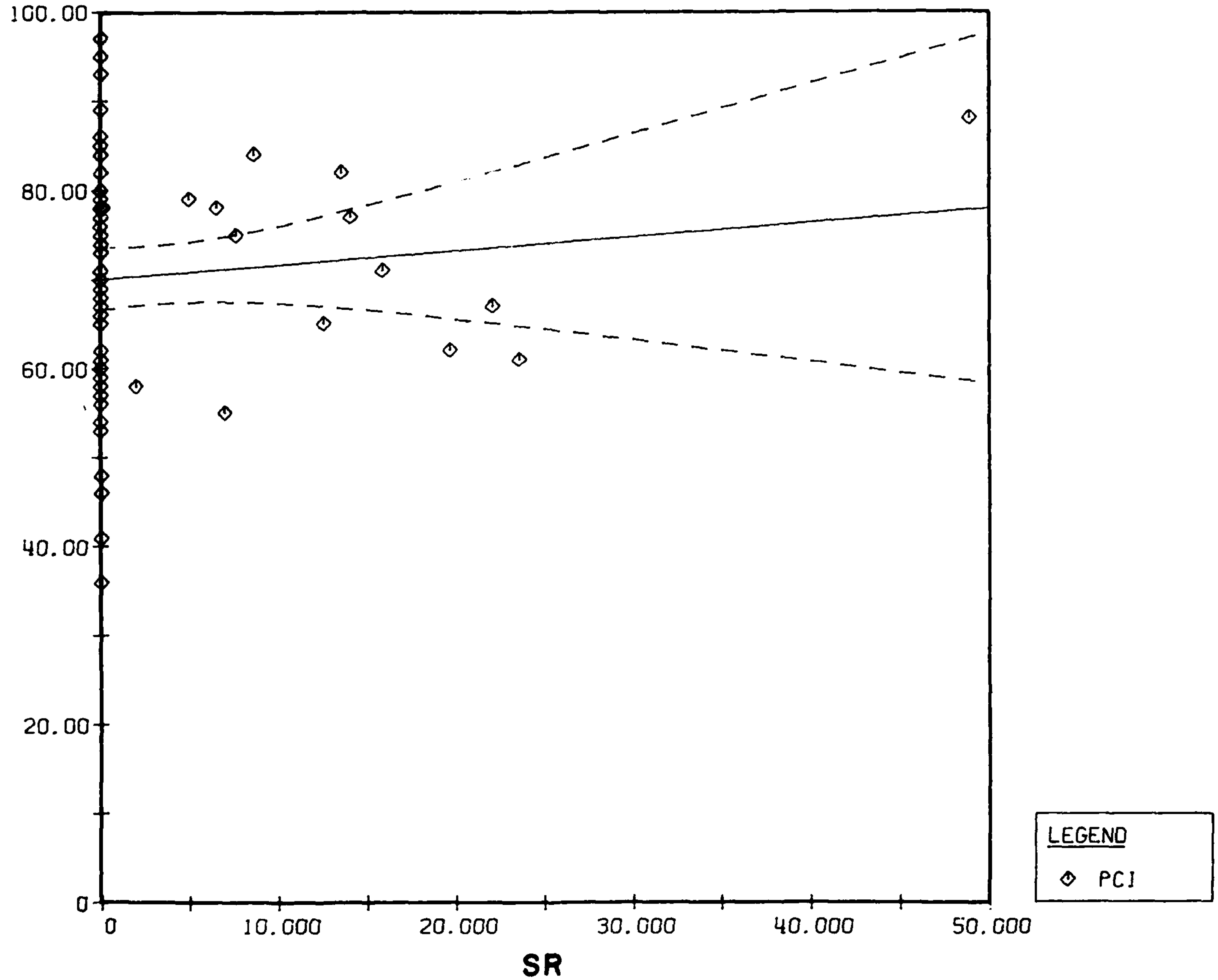


Figure 25. PCI Versus Slab Replacement for Plain-Jointed Concrete Airfield Pavement Features With and Without Asphalt Overlay.

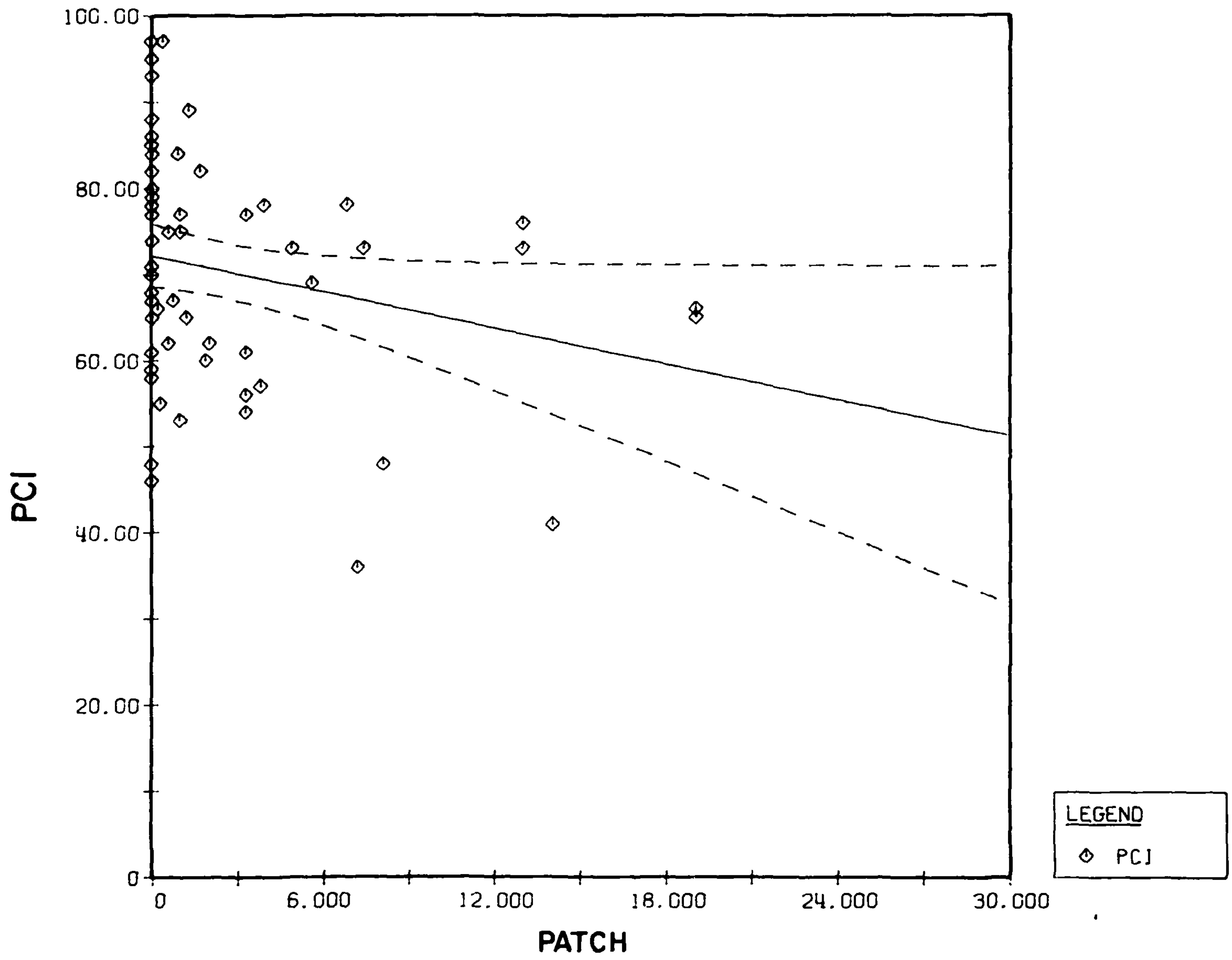


Figure 26. PCI Versus Percent of Slabs Patched for Plain-Jointed Concrete Airfield Pavement Features With and Without Asphalt Overlay.

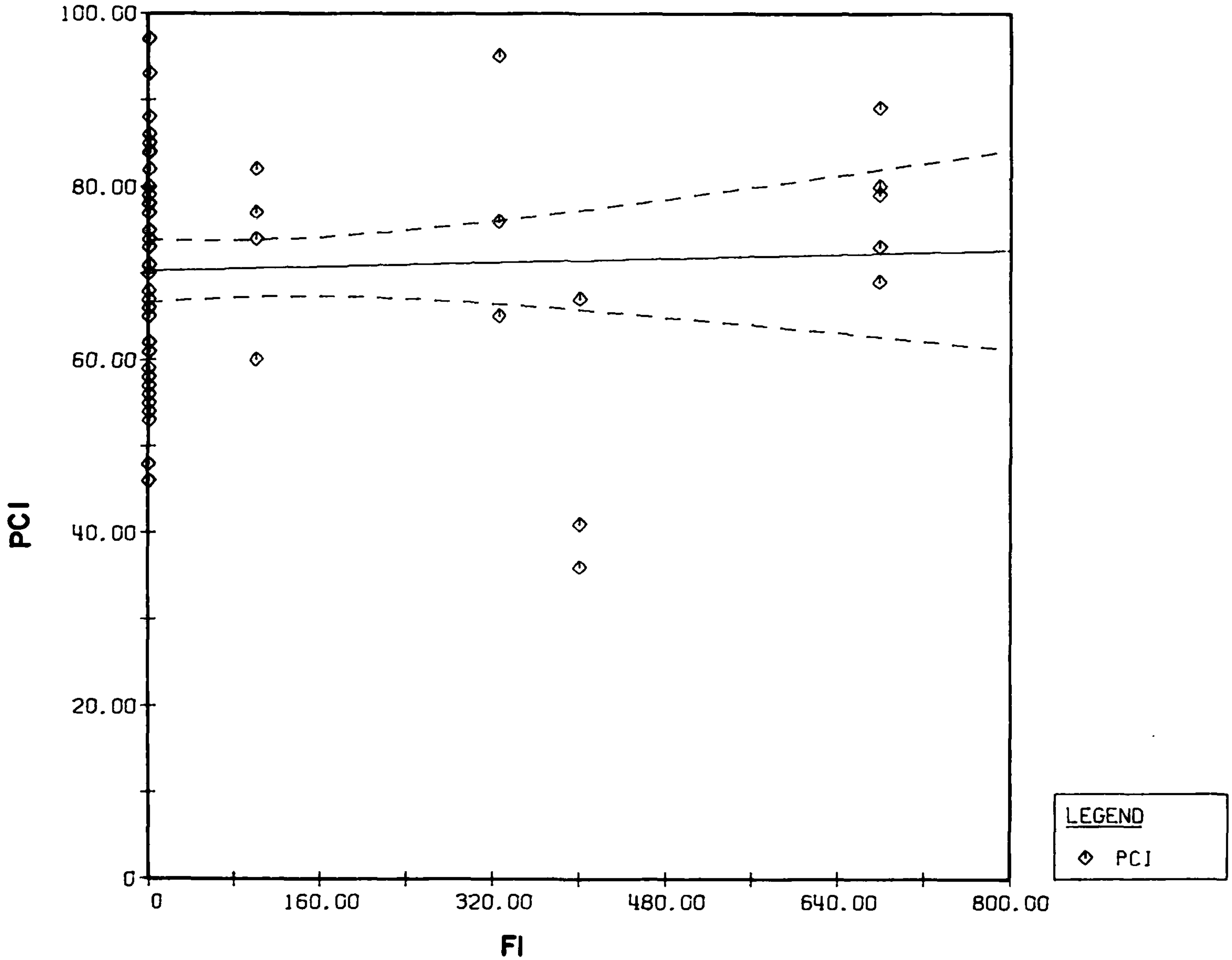


Figure 27. PCI Versus Freezing Index (FI) for Plain-Jointed Concrete Airfield Pavement Features With and Without Asphalt Overlay.

TABLE 16. CORRELATION MATRIX FOR VARIABLES USED IN PLAIN-JOINTED CONCRETE PAVEMENTS (n=91)

	Age	SLAB	SLAB OL	BASE	JSL	JSS	MR	K	PEI	ACWGT	FAT	FEAT	AREA	PS	FI	PPT	TEMP	SR	PATCH	ACOL	PCI
Age	1.0	-.24	-.23	-.11	-.21	-.24	.29	-.24	-.23	-.15	-.22	-.19	-.13	-.13	-.22	-.17	.27	.33	.10	-.45	-.42
SLAB		1.0	-.13	.42	.36	.52	.05	.07	.66	.73	-.25	-.18	-.21	-.21	.10	.12	-.22	-.23	.15	-.21	.33
SLAB OL			1.0	-.06	-.31	-.24	-.06	-.11	-.17	.05	.08	.07	.19	.04	0	.09	.02	-.05	.04	.38	.05
BASE				1.0	.39	.39	.24	.39	.30	.51	-.05	.03	-.20	-.25	.11	-.14	-.45	-.14	.16	.05	.01
JSL					1.0	.80	-.15	.12	.31	.33	.01	-.08	-.38	-.19	.09	-.07	.25	-.14	.12	-.13	-.18
JSS						1.0	-.05	.17	-.46	.40	-.08	.08	-.19	-.10	.17	-.14	.28	-.20	.06	-.11	.01
MR							1.0	.09	.18	-.15	-.51	-.12	.22	-.06	-.19	.05	0	.28	-.02	-.15	.23
K								1.0	.25	.17	.27	-.17	-.16	.13	.32	.09	-.30	-.17	.16	.14	.09
PEI									1.0	.37	-.37	-.07	-.40	-.15	-.06	.13	-.04	-.08	.36	-.64	.23
ACWGT										1.0	.23	.16	-.21	-.13	.38	-.04	-.50	-.21	.15	.07	.06
FAT											1.0	-.10	-.08	.19	.66	-.11	-.51	-.43	-.03	.52	-.23
FEAT												1.0	.27	-.21	-.03	.02	.02	-.08	-.16	.10	.16
AREA													1.0	-.25	-.07	-.06	.16	-.06	-.07	-.13	.12
PS														1.0	.27	-.13	-.13	-.10	-.17	-.13	-.01
FI															1.0	-.34	-.83	-.15	.08	.34	.04
PPT																1.0	.30	.07	-.01	-.02	.10
TEMP																	1.0	.10	-.10	-.32	-.01
SR																		1.0	-.10	-.18	.09
PATCH																			1.0	-.25	-.24
ACOL																				1.0	-.01
PCI																					1.0

TABLE 17. SUMMARY OF STEPWISE REGRESSION FOR PLAIN-JOINTED CONCRETE PAVEMENTS INCLUDING ASPHALT AND CONCRETE OVERLAYS (NUMBER OF FEATURES = 91)

Step	Variable	Entered or Removed	R^2	Standard Error
1	AGE	Entered	0.08	140.1
2	FAT*AGE	Entered	0.10	120.9
3	SR*AGE	Entered	0.13	120.0
4	ACOL x AGE	Entered	0.19	110.7
5	JSL*JSS*AGE	Entered	0.25	110.3
6	FI*AGE	Entered	0.28	110.1
7	PATCH*AGE	Entered	0.33	100.8
8	TEMP*AGE	Entered	0.37	100.5
9	PS*AGE	Entered	0.39	100.4
10	SLAB*AGE	Entered	0.40	100.4

$$PCI = 100.0 - AGE\,[0.01967FAT - 0.02408SR + 0.001051\,(JSL \times JSS) + 0.94191ACOL + 0.03475PATCH + 2.91238 - 0.001775FI - 0.04066TEMP] \qquad \text{[Equation 5]}$$

R^2 = 0.37 (adjusted for mean of dependent variable)

Standard Error = 10.5

N = 91 features

where: PCI = Pavement Condition Index at time AGE since construction or overlay with asphalt or concrete

AGE = time since construction of slab or, if overlaid, time since overlay construction (years)

FAT = (ratio of interior slab stress/modulus of rupture) x 100

SR = slab replacement (percent total slabs)

JSL = longest joint spacing (feet)

JSS = shortest joint spacing (feet)

ACOL = 1 if asphalt overlay exists
= 0 if no asphalt overlay exists

PATCH = slabs containing large patches (5 square feet), percent of total slabs, or percent area of total area patched if overlaid with asphalt

TEMP = average annual temperature (^{o}F)

FI = freezing index (degree days below 32^{o}F)

Equation 5 will be used in the various analyses discussed below. Figure 28 compares the predicted PCI with the measured PCI.

EVALUATION OF THE PCI PREDICTION MODEL (EQUATION 5)

Practically, the model (Equation 5) can be tested according to the following criteria:

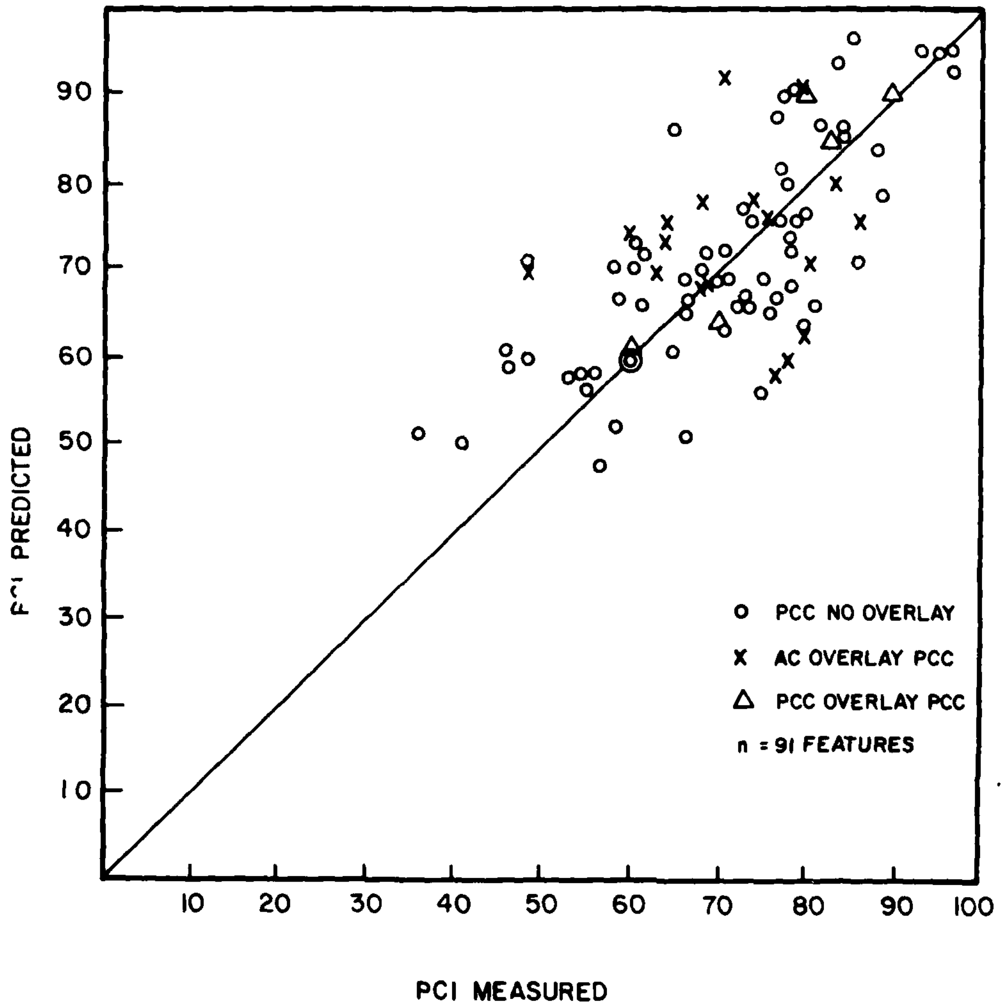


Figure 28. Comparison Between PCI Measured and PCI Predicted From Equation 5.

1. Does the model meet the appropriate boundary conditions? For example, when AGE = 0, or just after construction, the PCI should equal 100. The functional form of the model shows that this condition is satisfied. It also shows that as time increases, the PCI will decrease at a rate that depends on several important variables, including pavement structure and traffic.

2. Are the coefficients reasonable? Because the variables are intercorrelated, the coefficients of each independent variable do not exactly represent the independent influence that each variable has on the PCI. For example, to determine the exact influence of AGE on the PCI, the user cannot merely change AGE and hold all other variables constant to calculate the change in PCI, because other variables may change with AGE (such as patching and slab replacement). For example, if the change in PATCH and SR with AGE can be approximately estimated, then they can be varied with AGE and the true effect on PCI determined through a sensitivity analysis.

The sign of the coefficient is also very important, since it indicates the direction of change in the PCI caused by a change in any of the independent variables. For example, as AGE increases, the PCI decreases. This is a logical result, since all pavements deteriorate with time. As joint spacing increases, the PCI decreases, because the longer or larger the slab, the higher the thermal curling and moisture warping stresses which contribute to slab cracking. Several field and analytical studies have shown that longer joint spacing produces increased cracking (References 11 and 12).

The effects of TEMP and FI must be considered together, since they are highly correlated. Results show that pavements in relatively cold climates (FI is high and TEMP is low), such as the northern United States, have the highest PCIs. Pavements in the lower midsection of the United States (where FI is near zero) have the lowest PCIs. Pavements in the southern areas have PCIs that range between these two limits. For example, identical pavements subjected to the same traffic in the three areas listed below would have the following PCIs after 25 years:

	PCI	TEMP	FI
Wisconsin	75	45	1000
Missouri	40	55	0
Texas	55	70	0

These results are difficult to explain, but perhaps the low PCI in the midsection may be caused by the large number of freeze-thaw cycles that often result in concrete durability problems (i.e., "D" cracking). This distress has caused many problems in several midwestern states. There are fewer freeze-thaw cycles in colder than in warmer climates. The reason that pavements in the south have lower PCIs than those in the north may be related to the larger number of thermal gradients occurring in the south over the entire year (Reference 10).

Increasing the percentage of slabs replaced will increase the PCI, and increasing the percentage of slabs patched or the percentage of area patched for asphalt overlays will decrease the PCI, a result that appears to be contradictory. However, the reason for this is that features exhibiting

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Increasing the percentage of slabs replaced will increase the PCI, and increasing the percentage of slabs patched or the percentage of area patched for asphalt overlays will decrease the PCI, a result that appears to be contradictory. However, the reason for this is that features exhibiting significant deterioration have usually been patched previously. On the average, the PCI is significantly less for patched features, apparently because of the greater deterioration.

The PCI decreases as the ratio of stress/modulus of rupture x 100, or FAT, increases. This is a very logical trend, because the higher the ratio, the greater the fatigue damage from repeated aircraft traffic, which means that slab cracking will occur sooner. When an asphalt overlay is placed, its PCI decreases more rapidly than the PCI of the original concrete slab. This result is expected, since all of the cracks and joints in the concrete slab will soon reflect through the asphalt overlay and generally begin spalling. Therefore, all coefficients have logical and physically rational signs.

3. Is the equation plausible, i.e., how well does it represent a realistic situation? The equation would be plausible if all the variables affecting the PCI were included in the appropriate functional form. The PCI is a composite index of all existing pavement distress which is caused by or influenced by one or more of the following categories of variables: traffic, climate, materials, construction, concrete slab and subbase, foundation, previous maintenance, and overlay placement. Most of these categories are represented to some degree in Equation 5.

a. Traffic. The critical aircraft gear configuration and weight are included directly in the calculation of interior slab stress used to calculate FAT. The number of repeated loads is only indirectly considered through the AGE variable, since time is roughly proportional to accumulated aircraft passes. The number of passes would vary greatly between light-, medium-, and heavy-load aircraft, as well as between features.

b. Climate. Equation 5 includes the FI and TEMP variables, which are used to consider the influence of temperature on concrete slabs. The average annual precipitation (PPT) did not enter the equation, which is surprising, since moisture is believed to greatly affect pavement distress. However, the probable reason for this is because this variable correlates with FI and TEMP, i.e., there is higher annual rainfall in southern areas than in northern areas. In addition, the PPT may not be an adequate indicator of moisture effects. Often, local groundwater conditions or a "pumpable" softbase lead to fast deterioration, and these variables are not included in the equation.

c. Materials. The concrete modulus of rupture is the only slab/subbase material variable included. This variable is important, because it affects FAT, and consequently PCI. The k-value of the foundation is included as a material property, and is discussed under the foundation category below. Thus, there are considerable deficiencies in terms of material properties, since many additional material properties could affect the PCI.

d. Construction. The quality of construction is only considered through the mean concrete strength and layer thickness variables. Several factors are not considered, including variability of properties, air content, and quality of joint construction, because information was not available.

e. Concrete Slab and Subbase. This category is represented by the variables concrete slab thickness (as used to calculate FAT) and slab size or joint spacing (JSL x JSS), both of which significantly influence PCI. Other slab variables which influence this category include joint configuration and joint load transfer efficiency. All subbases for which data were available were granular. Even though subbase thickness was a variable, it did not enter the equation.

f. Foundation. This category is represented by the modulus of subgrade reaction (k-value), which is used to calculate interior slab stress, and thus FAT. This single parameter does not represent the entire influence of the foundation on pavement deterioration; other factors, such as soil type, expansion potential, moisture content, etc., may also be important.

g. Maintenance. The amount of previous repair affects the PCI. Two maintenance variables are included in the equation: large patches (PATCH) (greater than 5 square feet) and slab replacement (SR). Variables that were not included are joint and crack sealing and small patches.

h. Overlay. The 91 pavement features from which Equation 5 was developed included 19 asphalt overlays and 5 concrete overlays. These data are designated by special symbols in Figure 29. The mean age of the asphalt overlays is approximately 10 years, and the general grouping of data is lower than the nonoverlaid pavements, which explains why the AC or variable entered Equation 5. Thus, asphalt overlays are not performing as well as the original concrete slabs.

More data are needed to determine the long-term influence of time on the PCI of asphalt overlays; however, the concrete overlays appear to be performing as well as or better than the nonoverlaid pavements.

While Equation 5 contains several variables that affect PCI, many others also known to influence it are not included. However, the equation is expected to reproduce or model some of the major aspects of pavement deterioration.

4. Is the model usable? Equation 5 has several deficiencies, including the fact that it is based on an insufficient data base. Nevertheless, the following analysis shows that the equation has several important potential uses. First, a sensitivity analysis was conducted using the equation to show the general influence of the variables on PCI. The following typical pavement feature was selected:

	Mean	Range
SLAB	16 inches	6-23 inches
K	350 pounds/cubic inch	50-500 pounds/cubic inch
MR	700 psi	500-900 psi
JSL & JSS	25 x 25 feet	25 x 25 to 15 x 12.5 feet
ACWGT	--	light, medium, heavy
TEMP	63 ^{O}F	--
FI	0 degree days below 32 ^{O}F	--
SR	0%	0

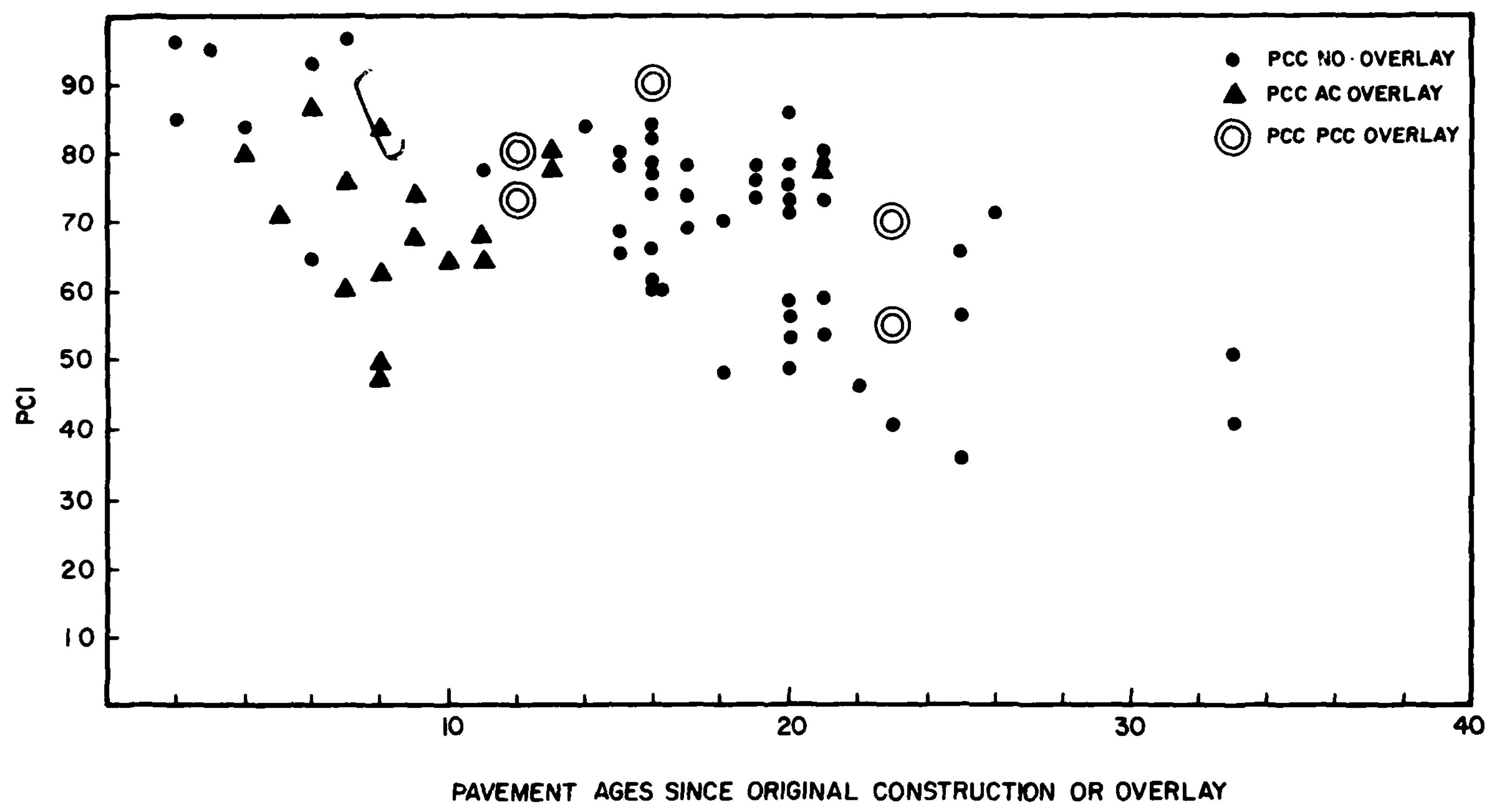

Figure 29. PCI Versus Age for Asphalt Overlays, Concrete Overlays, and Nonoverlaid Pavements.

PATCH varied according to PCI:

PCI	PATCH
0-29	10
30-39	8
40-49	4
50-59	2
60-100	0

Using Equation 5, graphs were prepared in which slab thickness, modulus of rupture, k-value, slab size, and aircraft type (and weight) were varied over typical values found in the field (see Figures 30 through 33). It was noted that after 25 years of service, slab thickness dramatically influences the PCI, particularly slabs less than 15 inches thick. The aircraft type (or weight) also greatly influences the PCI, particularly for thinner slabs. As the slab becomes thicker, the influence of aircraft greatly diminishes, because the damage caused by high-load stress is much less significant on a thicker slab. The k-value has a smaller influence than slab thickness on PCI (although its influence is much greater for values less than 200 pounds/cubic inch than for those more than 200 pounds/cubic inch and for medium to heavy aircraft). Slab size significantly influences the PCI; i.e., the larger the slab is, the less the PCI will be, because larger slabs display an increased tendency to crack when subjected to increased thermal and moisture gradient stresses. These stresses increase greatly as joint spacing increases; e.g., from 15 to 25 feet (Reference 11). Decreasing the spacing from 25 to 15 feet will make the PCI after 25 years approximately 18 points higher. Increased cracking will lower the PCI. The concrete modulus of rupture is a significant influence for the medium- and heavy-load aircraft, but not for the light-load aircraft because of the higher load-fatigue damage resulting from the heavier aircraft. These results appear to be reasonable.

Next, an analysis was conducted to illustrate the use of Equation 5 for predicting the consequences of maintenance and repair decisions. The following typical pavement feature was used for the analysis:

AGE	= 15 years	MR	= 700 psi
PCI	= 75	ACWGT	= 60 kips (fighter)
SLAB	= 10 inches	PATCH	= 0%
K	= 200 pounds/cubic inch	SR	= 0%
JSL	= 15 feet	FI	= 0 degree days below 32^{o}F
JSS	= 12.5 feet	TEMP	= 55^{o}F

a. If routine maintenance were continued as in previous years, when would the pavement require rehabilitation? Assume that rehabilitation is needed when the PCI = 40.

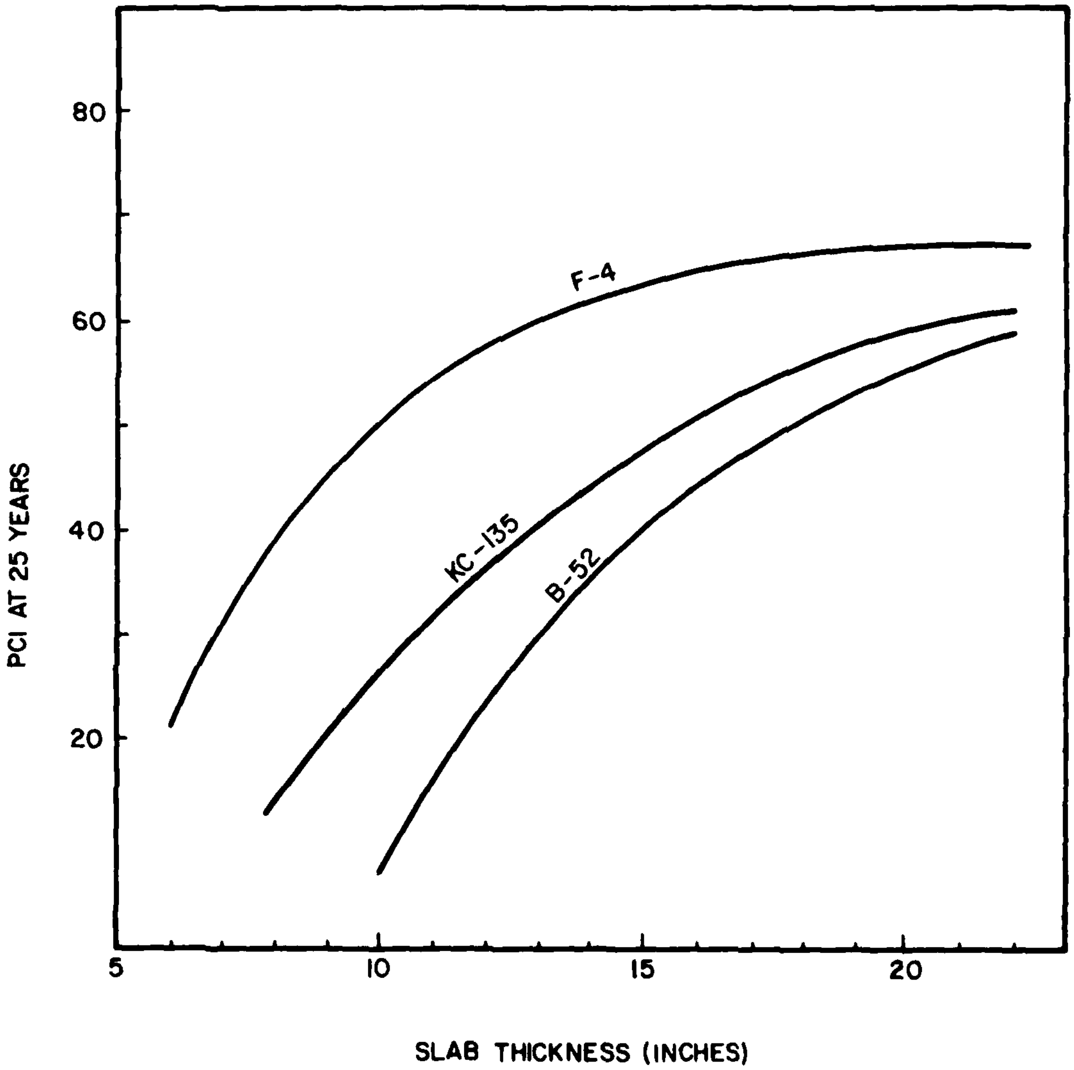

Figure 30. Influence of Slab Thickness on the PCI After 25 Years of Service.

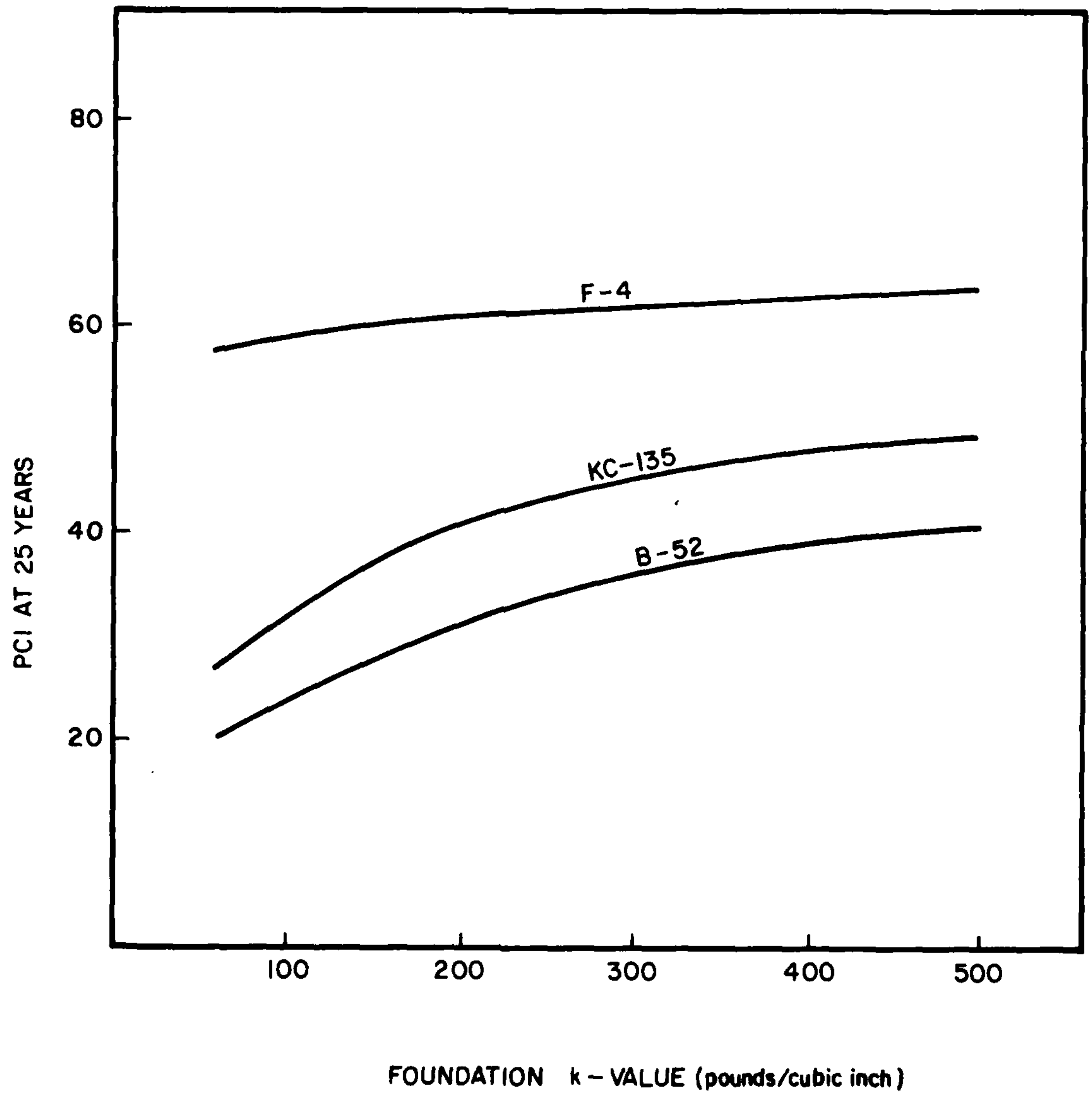

Figure 31. Influence of k-Value on the PCI After 25 Years of Service.

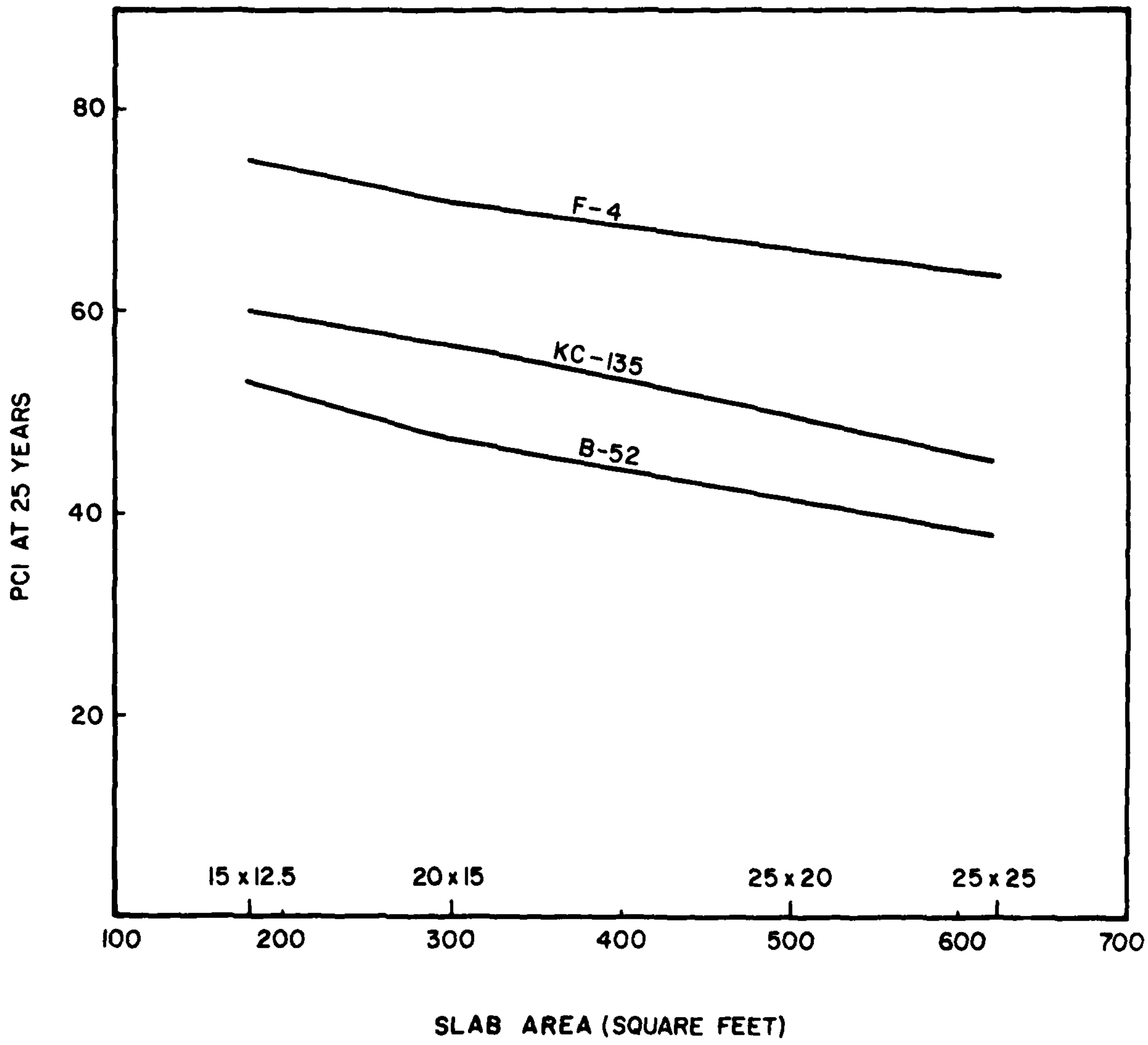

Figure 32. Influence of Slab Size on the PCI After 25 Years of Service

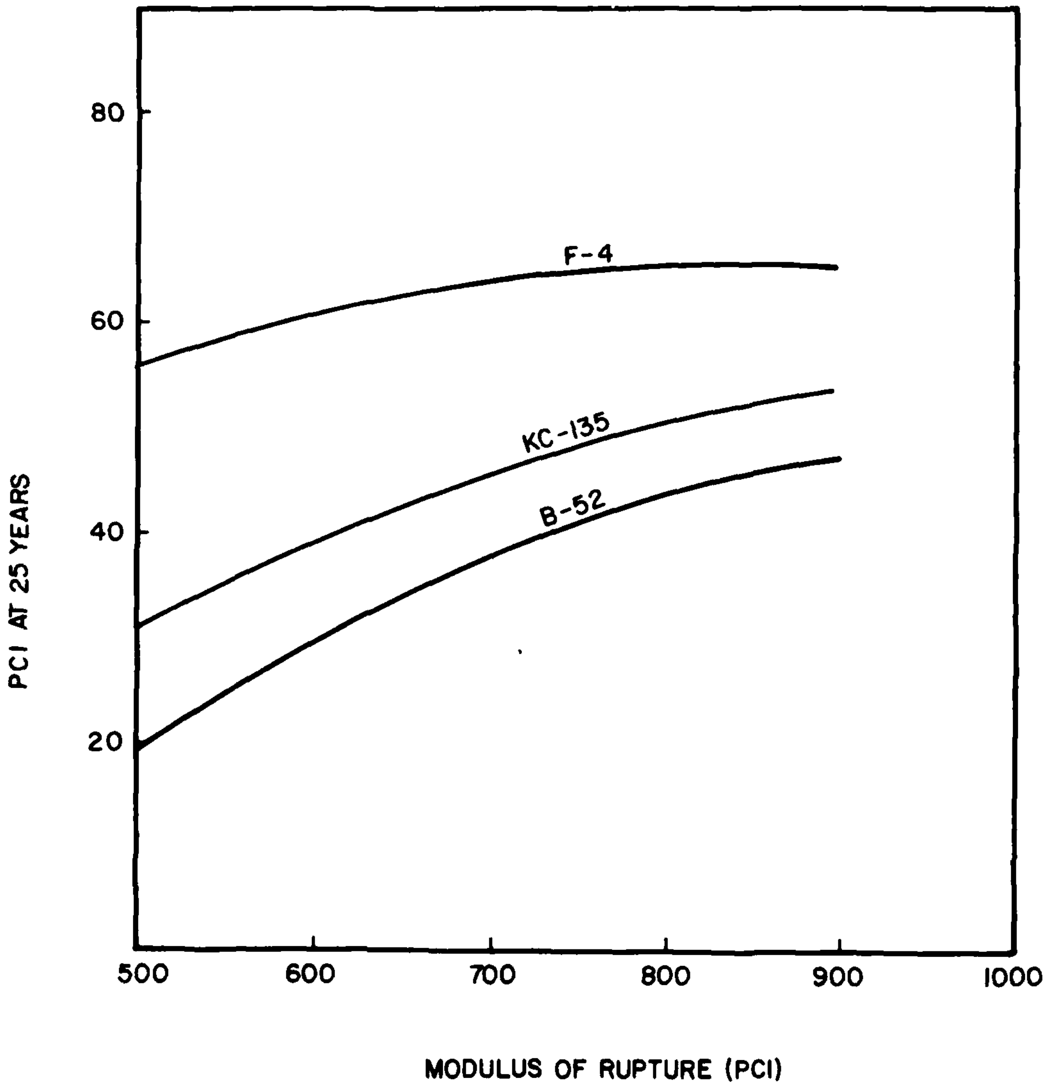

Figure 33. Influence of Modulus of Rupture on the PCI After 25 Years of Service.

First calculate the FAT:

$$FAT = \frac{\text{interior stress*}}{\text{modulus of rupture}} \times 100 = \frac{320 \times 100}{700} = 46.$$

Adjust Equation 5 to "fit" the specific age and PCI of the pavement:

$$PCI = 100 - AGE\ [0.01967FAT - 0.02408SR + 0.9419ACOL + 0.001051(JSL \times JSS) - 0.001775FI - 0.04066TEMP + 0.034748PATCH + 2.91238]C$$

where:

PCI = 75	SR = 0	TEMP = 55
AGE = 15	FAT = 46	FI = 0
JSL = 15	PATCH = 0	ACOL = 0
JSS = 12.5	SLAB = 10	

Thus, C = 0.937 (this factor must be used with Equation 5 for this particular pavement feature, so that the PCI at 15 years is 75).

Now using Equation 5 and including C, the AGE when the PCI = 40 can be computed (PATCH = 5 percent, which is assumed for a PCI of 40):

$$40 = 100 - AGE\ [1.9517]\ 0.937$$

$$AGE = 33 \text{ years.}$$

Thus, the pavement is expected to need rehabilitation in approximately 33 - 15 = 18 years from the present.

b. If 15 percent of the slabs are replaced, when will the pavement need rehabilitation? Using SR = 15 percent, Equation 5 is resolved for the time when PCI = 40:

$$40 = 75 - TIME\ [0.01967 \times 46 - 0.02408 \times 15 + 0.001051 \times 15 \times 12.5 - 0.04066 \times 55 + 0.034748 \times 5 + 2.91238]\ 0.937$$

$$TIME = 23 \text{ years from present.}$$

Thus, the slab replacement program extends the life by 23 - 18 = 5 years, or 28 percent. Note that 75 was used instead of 100 because this is the existing PCI of the pavement.

* Note: Interior-stress determined from Figure 7.

c. If the mission aircraft is changed from fighter (light load) to medium-load cargo with a gross aircraft load of 335 kips, when will the pavement need rehabilitation? First, calculate the FAT for the new aircraft:

$$\text{FAT} = \frac{650^{*}\text{ psi}}{700\text{ psi}} \times 100 = 93$$

Equation 5 is now solved for TIME until PCI = 40:

$$\begin{aligned}40 = 75 - \text{TIME}\ [&0.01967 \times 93 - 0.02408 \times 0 + 0.9419 \times 0 \\ &+ 0.001051 \times 15 \times 120.5 - 0.001775 \times 0 - 0.04066 \times 55 \\ &+ 0.034748 \times 5 + 2.91238]\ 0.937\end{aligned}$$

TIME = 13 years from present.

Thus, with the medium-load traffic, the time until rehabilitation is now expected to be 13 years instead of 18 years, a life decrease of 28 percent.

d. If the mission aircraft was changed from the fighter to the C-141, with a gross weight of 300 kips, and an asphalt overlay of 5 inches was proposed, would this design last another 20 years until the PCI = 40?

First compute FAT for the C-141, assuming a slab thickness of 10 + 5 = 15 inches.

$$\%\text{ AC of total} = \frac{5 \times 100}{15} = 33.3$$

Thus, from Equation 1: $Y = 1.00 + 0.0143 \times 33.3$
$= 1.476$

Interior stress for 15 inches of PCC from Figure 9 is 360 psi. Adjusting this stress for the 5 inches of asphalt overlay:

360 x 1.476 = 531 psi (stress at bottom of a 10-inch slab with a 5-inch asphalt overlay)

The FAT for the C-141 is calculated as follows:

$$\text{FAT} = \frac{531}{700} \times 100 = 76$$

*Note: Interior stress determined from Figure 9.

The time until PCI = 40 is now computed as:

$$40 = 100 - AGE\,[0.01967 \times 76 + 0.001051 \times 15 \times 12.5 - 0.04066 \times 55 + 0.9419 \times 10.0 + 0.034748 \times 5 + 2.91238]\,0.937$$

AGE = 18 years from present.

Note that 100 is used because the PCI will be 100 after the overlay is placed. Thus, for the C-141, an overlay of 5 inches of AC will not extend the life for 20 years, because another overlay will be required after 18 years. Considerable additional work is needed to study this important aspect more adequately, so that life predictions of overlays can be conducted more accurately.

DEVELOPMENT OF SLAB CRACKING PREDICTION MODEL

Slab cracking is the most serious distress found in plain-jointed concrete pavements. Thus, if a predictive equation could be developed for slab cracking, it would be useful to personnel making M&R decisions. Data were collected from the 67 plain-jointed concrete pavements. Cracking was defined as percent slabs having either corner breaks, longitudinal and transverse cracking, or divided or shattered slabs. The stepwise regression procedures were used to develop a predictive model for slab cracking. Table 18 summarizes the stepwise regression results. Very little improvement in the equation occurs after the sixth step. However, if the user wishes to include only those variables whose estimated coefficients are significant at the 0.05 level, then only the variables contained in the first five steps should be used. Thus, the following predictive equation is obtained:

$$CRACK = AGE\,[0.02652\,TEMP - 0.03183\,SR - 0.147\,SLAB + 0.00236\,(JSL \times JSS) + 0.9191\,AREA]. \qquad \text{[Equation 6]}$$

Statistics: $R^2 = 0.44$

Standard Error = 14.5

n = 67 features (no overlays included)

where:
- CRACK = slab cracking (percent of total slabs)
- AGE = time of original construction of slab (years)
- TEMP = average annual temperature (^oF)
- SR = slab replacement (percent of total slabs)
- SLAB = thickness of concrete (inches)
- JSL = longest joint spacing (feet)
- JSS = shortest joint spacing (feet)
- AERA = 1 for an A traffic area, 0 for B or C traffic areas.

TABLE 18. RESULTS FROM STEPWISE REGRESSION FOR SLAB CRACKING (n = 67) FOR PLAIN-JOINTED CONCRETE

Step	Variable	Entered or Removed	R^2	Standard Error
1	TEMP x AGE	Entered	0.17	170.0
2	SR x AGE	Entered	0.23	160.5
3	SLAB x AGE	Entered	0.28	160.2
4	JSL x JSS x AGE	Entered	0.38	150.1
5	AREA x AGE	Entered	0.44	140.5
6	K x AGE	Entered	0.46	140.4
7	PPT x AGE	Entered	0.46	140.4
8	PATCH x AGE	Entered	0.47	140.4
9	FI x AGE	Entered	0.48	140.4
10	PPT x AGE	Removed	0.48	140.3
11	FAT x AGE	Entered	0.49	140.3

Equation 6 can be tested according to the following criteria:

1. Does the model meet the appropriate boundary conditions? One boundary condition is that when AGE = 0, the CRACK = 0, assuming good construction practice. Also, as AGE increases, the slab cracking should increase. Both of these conditions are met in Equation 6.

2. Are the coefficients reasonable? The sign of the coefficient, and thus its directional effect on CRACK, can be compared to what is physically reasonable. As AGE increases, the CRACK also increases at a rate that depends on several independent variables. This is physically explainable, since AGE represents such variables as accumulated aircraft passes and daily thermal gradient cycles, which eventually lead to slab cracking. As TEMP increases, CRACK increases, which indicates that slabcracking is greater in warmer climates than in colder climates. Assuming that thermal gradients are a significant cause of slab cracking, it can be shown that slabs in warmer climates undergo many more cycles of high thermal gradients than slabs in colder climates (Reference 11). This occurs because the slabs in colder climates have very small gradients during the winter months, since there is reduced sunshine (and solar radiation).

As slab replacement (SR) increases, CRACK decreases. The most common reason for SR is serious slab cracking. Thus, the result of SR would be a reduction in the amount of cracking. As SLAB (slab thickness) increases, CRACK decreases, because SLAB has a great influence on load stress damage. An increase in SLAB also reduces the thermal gradients through the slab, which reduces cracking potential. As slab size increases (JSL x JSS), CRACK also increases, a natural result of the greatly increased thermal curl and moisture warping stress which occurs when slab size is increased. Slabs located in A traffic areas tend to crack more than those in B or C areas, possibly because there is greater channelization of traffic in A areas.

3. Is the equation plausible, i.e., how well does the equation represent a realistic situation? The equation is plausible if all variables affecting CRACK were included in their appropriate functional forms. Many factors affect cracking, including traffic, climate, materials, construction, concrete slab dimensions, foundation, and previous maintenance. These factors are discussed in the following subsections.

a. Traffic. It is significant that the variable FAT did not enter the equation, since aircraft loadings probably have an important influence on CRACK. FAT may not have entered the equation because it correlates highly with other variables such as SLAB. Additional study is needed here because it appears that Equation 6 is deficient without the FAT variable; the variables included in the equation that relate to traffic are AREA1 (channelization) and AGE (accumulated aircraft passes).

b. Climate. TEMP is the only variable that directly considers climate. AGE may be considered to provide an indication of the relative number of cycles of thermal gradient reversals (i.e., day and night).

c. Materials. There are no variables that consider material properties.

d. Construction. There are no variables that consider construction quality.

e. Concrete Slab Dimensions. SLAB and JSL x JSS adequately represent the slab dimensions.

f. Foundation. There are no variables that consider foundation.

g. Previous Maintenance. SR is the only variable representing previous maintenance.

As shown in the discussion above, Equation 6 has numerous deficiencies for predicting slab cracking; however, those variables that entered the equation provide a reasonable prediction of cracking as is subsequently shown in Figures 34 and 35. An expanded data base and much additional work are needed before a totally acceptable equation is available.

4. Is the model usable? A small sensitivity analysis (Figures 34 and 35) illustrates the effect that the variables have on CRACK. The same pavement feature used in the subsection dealing with the development of the PCI prediction model is used. Figures 34 and 35 show the relative influence of the annual average temperature, slab size, and slab thickness on the slab cracking after 25 years, when all other variables are held constant. All of the plots are linear, since the regression model developed was a linear model. In reality, the results are probably curvilinear. These plots should be considered only as general approximations to actual relationships, although they do illustrate overall effects.

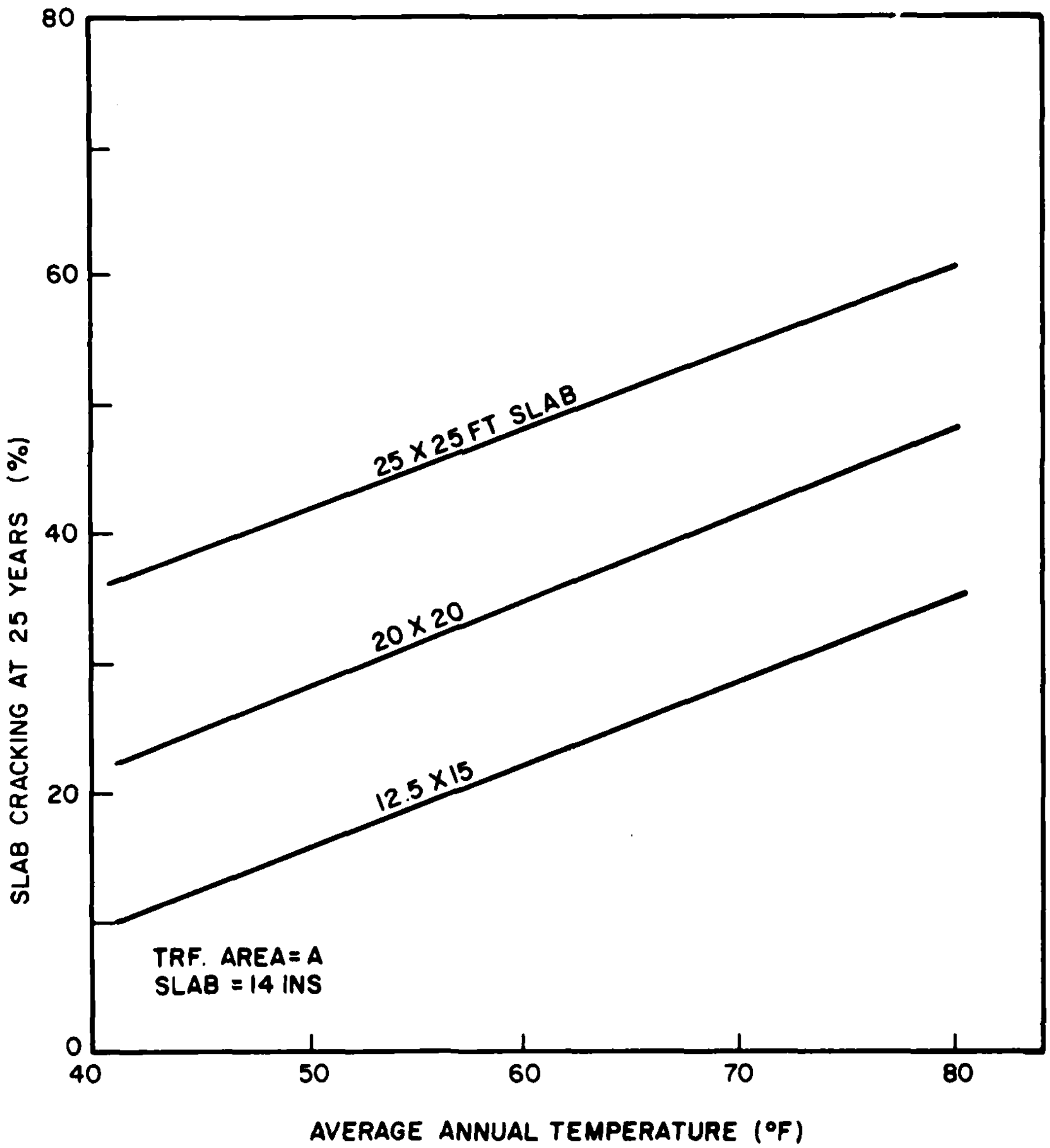

Figure 34. Influence of Temperature and Slab Size on Slab Cracking After 25 Years.

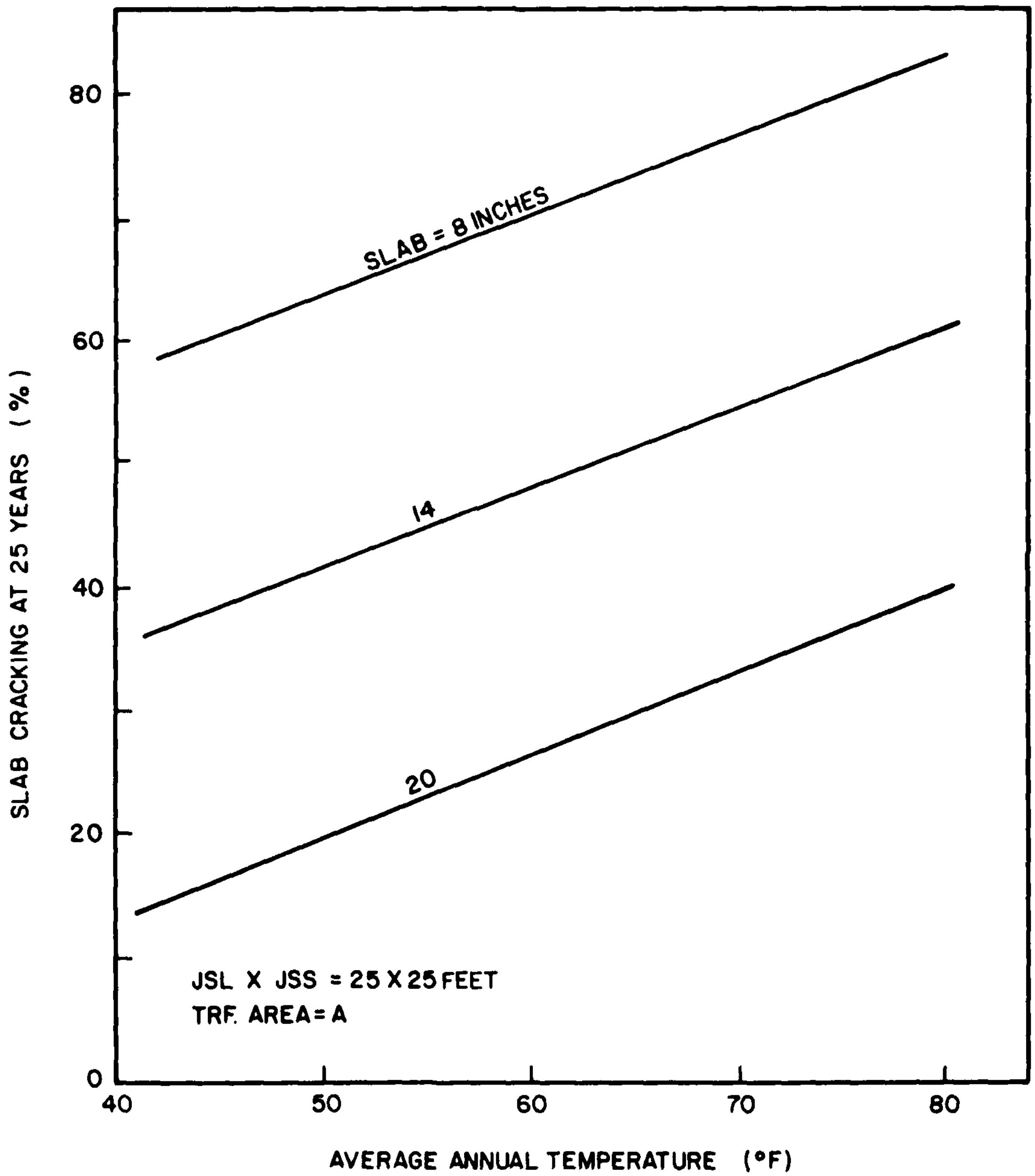

Figure 35. Influence of Temperature and Slab Thickness on Cracking After 25 Years.

SECTION IV

ASPHALT PAVEMENT PCI AND DISTRESS PREDICTION

The objective of the PCI and distress prediction models is to forecast the condition of pavement for a variety of possible future M&R alternative actions and/or mission changes. The models are to be used by administrators and engineers for different purposes, including decision-making regarding mission of the airfield, determination of budget requirements, and optimization of maintenance funds.

This section describes three models for predicting PCI of asphalt pavements, and one model for predicting alligator cracking, which is a major structural distress. The three PCI models include pavements that have not received overlay since the original construction, pavements that have received AC overlay, and a combination of both types. Model development was limited by the amount and type of data available as well as by time constraints. Therefore, the models should be considered tentative until further data are obtained and the models are tested, improved, and verified.

PCI PREDICTION -- ORIGINAL CONSTRUCTION MODEL (NO OVERLAYS)

The first step in model development was to identify all major factors believed to significantly influence pavement deterioration. This was achieved through a literature review, interviews with major command and base pavement engineers, and the previous experience of the project staff. The availability, cost, and time to obtain each variable for each airfield pavement feature was assessed, and it was concluded that several variables could not be obtained within the limitations imposed by the available resources. Table 19 presents a list of variables used to develop the models. Some variables believed important, but not used, included tensile strain at the bottom of the AC surface layer, vertical stress on top of the subgrade, and aircraft traffic volume. Available data were reviewed for completeness and accuracy, and five data points were then eliminated. The usable data were taken from 26 pavement features (Appendix B).

The computerized SPSS (Reference 13) was used for all data analysis. A correlation matrix (Table 20) which included the dependent variable (PCI) and the independent variables (such as age and thickness) was first obtained and analyzed to identify significant correlations. Figures 36 through 38 present several plots of variables having the highest correlation with the PCI. The stepwise regression technique was then used to develop a PCI prediction model. In developing the model, the independent variables were introduced to interact with pavement age. This interaction had the advantage of insuring that at age zero, the PCI would equal the maximum value. The maximum value was set at 100 by forcing the regression through the origin. Selected correlation plots of independent variables times age and the PCI are presented in Figures 39 and 40. Because of time constraints, interactions among other variables and possible transformations of independent variables (i.e., x^2 or Log x instead of x) were not examined.

TABLE 19. LIST OF INDEPENDENT VARIABLES OF ASPHALT PAVEMENT

AC (No overlay)

AGEOR (Ages of Pavement) -- Years
TAC THICK (Total AC Thickness) -- Inches
B THICK (Base Thickness) -- Inches
SB THICK (Subbase Thickness) -- Inches
B CBR (Base CBR) -- Percent
SB CBR (Subbase CBR) -- Percent
SG CBR (Subgrade CBR) -- Percent
ACWGT (Aircraft Weight) -- kips
AREA (Traffic Area, Type A=1, Type B=2, Type C=3)
P/S (Primary=1, Secondary=2)
Feat (Feature, Apron=1, Taxiway=2, Runway=3)
ZONE (Environmental Zone:
Wet, Freeze=1, Seasonally Wet, Freeze=2
Dry, Freeze=3, Wet, Freeze-Thaw=4,
Seasonally Wet, Freeze-Thaw=5, Dry, Freeze-Thaw=6,
Wet, No Freeze=7, Seasonally Wet, No Freeze=8,
Dry, No Freeze=9)
FI (Freezing Index, Degree Days (Below 32^oF)
PPT (Precipitation) -- Inches
AAT (Annual Average Temperature) -- ^oF
ADTR (Annual Daily Temperature Range) -- ^oF
AATR (Annual Average Temperature Range) -- ^oF
R_{AC} (Load Repetition Factor for AC Thickness/Interface Base)
R_{SG} (Load Repetition Factor for Subgrade)
T Equiv Thick (Total Equivalent Thickness of Pavement) -- Inches
R Equip Thick (Load Repetition Factor for Total Equivalent Thickness of Pavement)
TA (Total Alligator Cracking) -- Percent of Sample Units
PATCH (PATCHING) -- Percent of Sample Unit

AC pavement with AC overlay

Variables for computing PCI prediction model were the same as the AC pavement variables with no overlay plus four more variables: AGEOL, AGECOL, ACOL Thick, and TAC Thick.

AGEOL (Age after Overlay) -- Years
AGECOL (Age between Original Construction and Overlay) -- Years
ACOL Thick (AC Thickness for Overlay) -- Inches
TAC Thick (Total AC Thickness) -- Inches

Age (Age after Original Construction or Overlay) -- Years

TABLE 20. CORRELATION MATRIX FOR ASPHALT PAVEMENTS (NO OVERLAYS)

	Age	AC THICK	B THICK	SB THICK	B CBR	SB CBR	SG CBR	ACWGT	AREA	P/S	FEAT	FI	PRECI	AA TEMP	ADTR	AATR	σ_{AC}	σ_{SG}	T Equiv Thick	α Equiv Thick	TA	PATCH	PCI
Age	1.0	.28	.09	-.11	-.27	-.25	.19	.20	-.66	.01	-.33	.14	.36	-.25	-.52	.10	.14	.01	-.05	0	.17	-.10	-.39
AC THICK		1.0	.01	-.40	-.76	-.29	.19	.09	.15	-.18	.33	-.04	.19	.12	-.08	-.28	-.05	-.07	-.21	-.01	-.22	-.13	.26
B THICK			1.0	.30	-.05	-.07	-.33	.38	.14	-.27	.34	-.07	-.11	-.19	.07	0	-.05	-.23	.70	-.30	.10	.46	-.04
SB THICK				1.0	.50	.62	-.56	.47	-.26	-.14	.06	.13	-.48	-.48	.47	.46	-.19	-.24	.87	-.42	.59	.26	-.33
B CBR					1.0	.52	-.02	0	-.36	-.03	-.39	.18	-.22	-.18	.05	.23	.19	.15	.34	.17	.22	.08	-.15
SB CBR						1.0	-.44	.01	-.11	-.26	.22	.03	-.54	-.25	.55	.45	.22	.34	.46	.20	.16	.26	.11
SG CBR							1.0	-.05	-.12	.34	-.47	.14	.61	.40	-.60	-.61	-.11	.21	-.55	.41	-.13	-.33	[illegible]
ACWGT								1.0	-.20	-.06	.27	.60	-.05	-.65	-.07	.15	-.68	-.69	.58	-.73	.68	.38	-.65
Area									1.0	.01	.60	-.45	.07	.46	.27	-.32	-.19	-.04	-.10	-.02	-.27	.24	.37
P/S										1.0	-.40	-.14	.35	.31	-.15	-.52	.30	-.07	-.28	-.01	-.09	-.02	-.33
FEAT											1.0	.01	-.30	-.21	.41	.12	-.27	-.24	.26	-.34	.04	.42	.20
FI												1.0	-.29	-.75	-.20	.28	-.29	-.31	.09	-.31	.27	.15	-.30
PRECI													1.0	.33	-.81	-.47	-.14	-.07	-.41	.06	-.03	.05	-.33
AA TEMP														1.0	.08	-.62	.25	.43	-.45	.59	-.44	-.26	.31
ADTR															1.0	.24	-.03	.10	.39	-.03	.03	-.04	.31
AATR																1.0	.13	-.05	.32	.29	-.05	-.01	-.08
σ_{AC}																	1.0	.64	-.16	.68	-.46	-.26	.58
σ_{SG}																		1.0	-.31	.94	-.51	-.01	.44
T Equiv Thick																			1.0	-.44	.50	.41	-.23
α Equiv Thick																				1.0	-.54	-.14	.44
TA																					1.0	14	-.78
PATCH																						1.0	-.27
PCI																							1.0

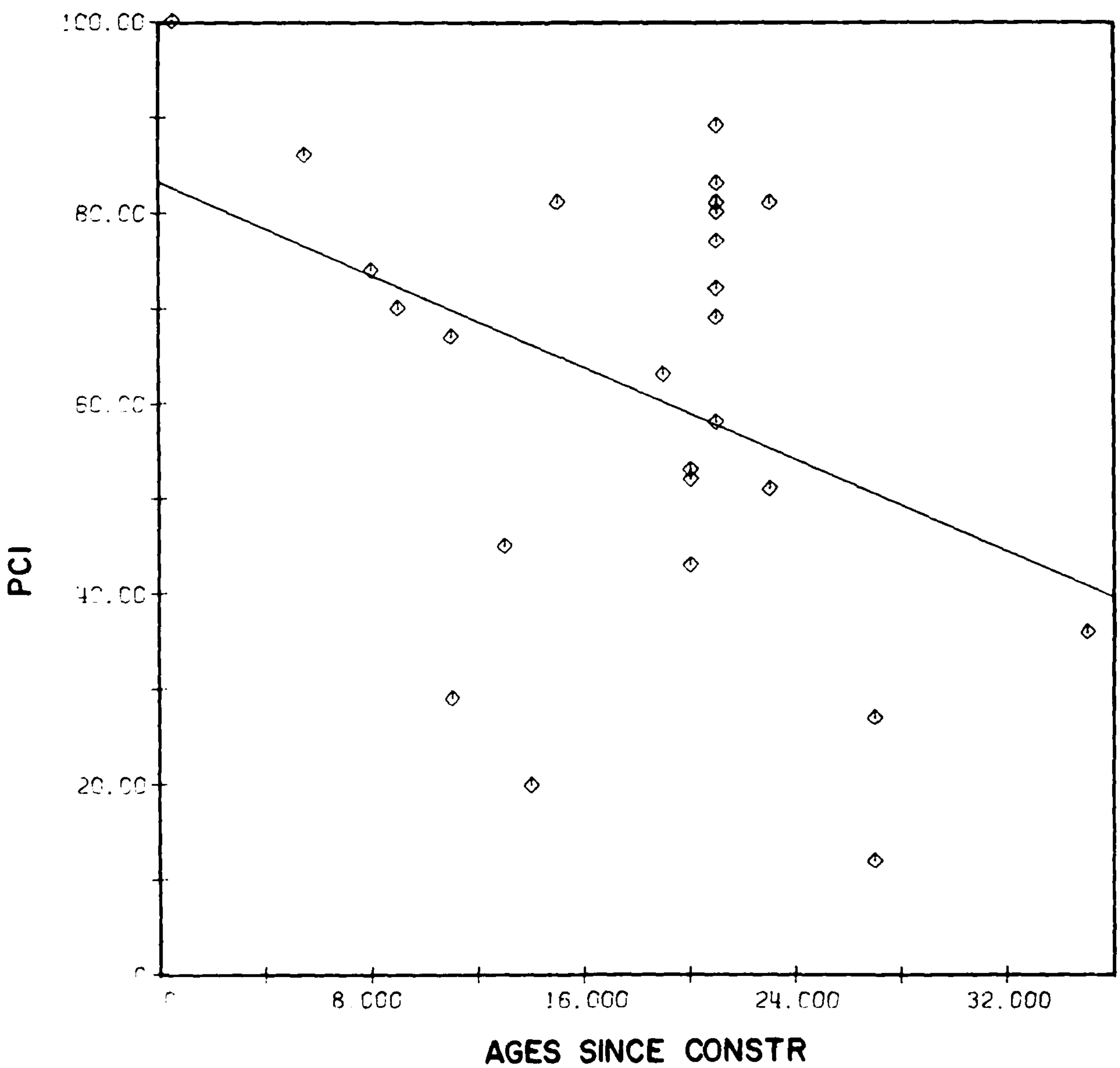

Figure 36. Correlation Between PCI and Age Since Original Construction for Asphalt Pavements (No Overlay).

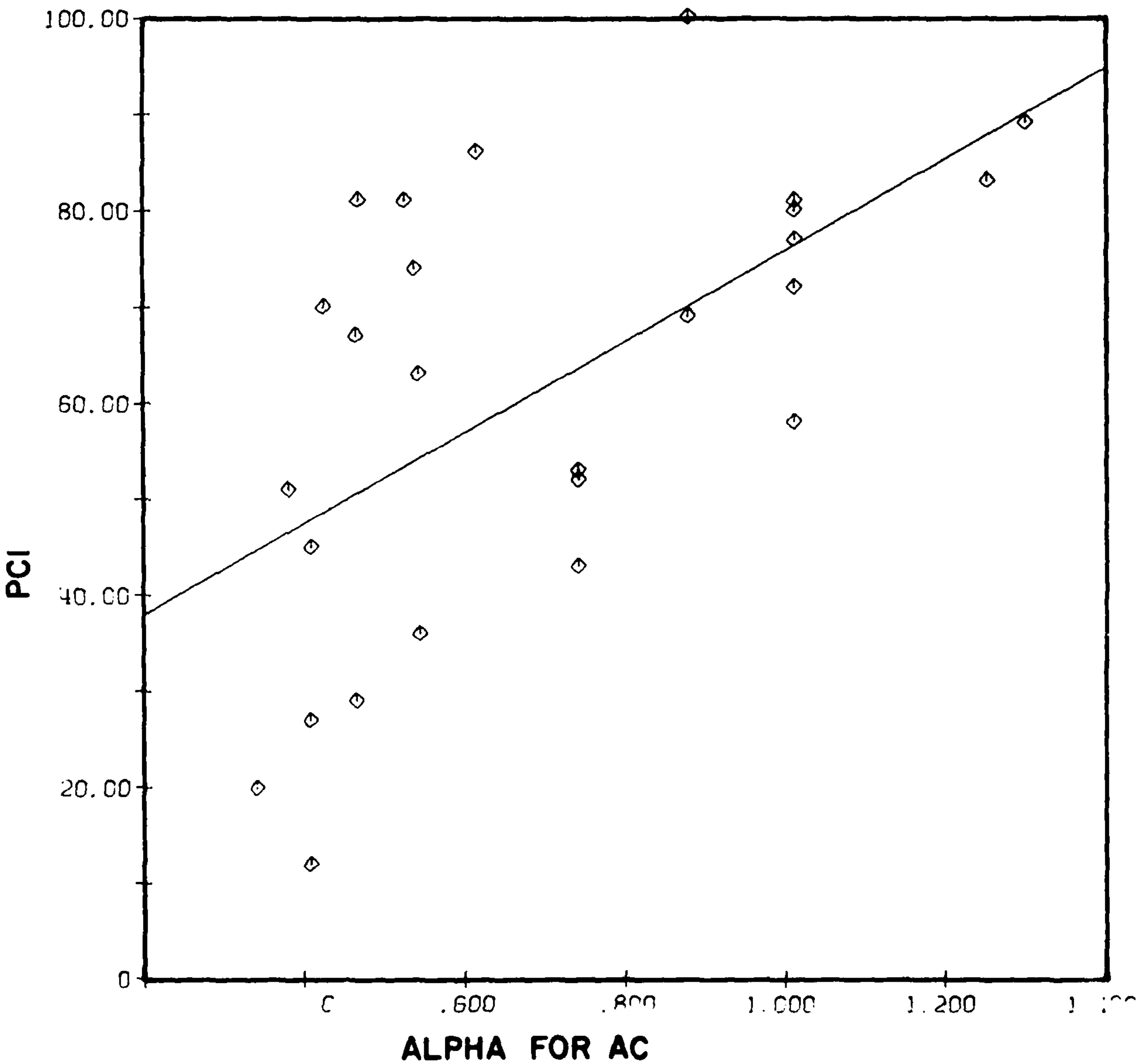

Figure 37. Correlation Between PCI and Load Repetition Factor Computed at Surface/Base Interface (α_{AC}) for Asphalt Pavements (No Overlay).

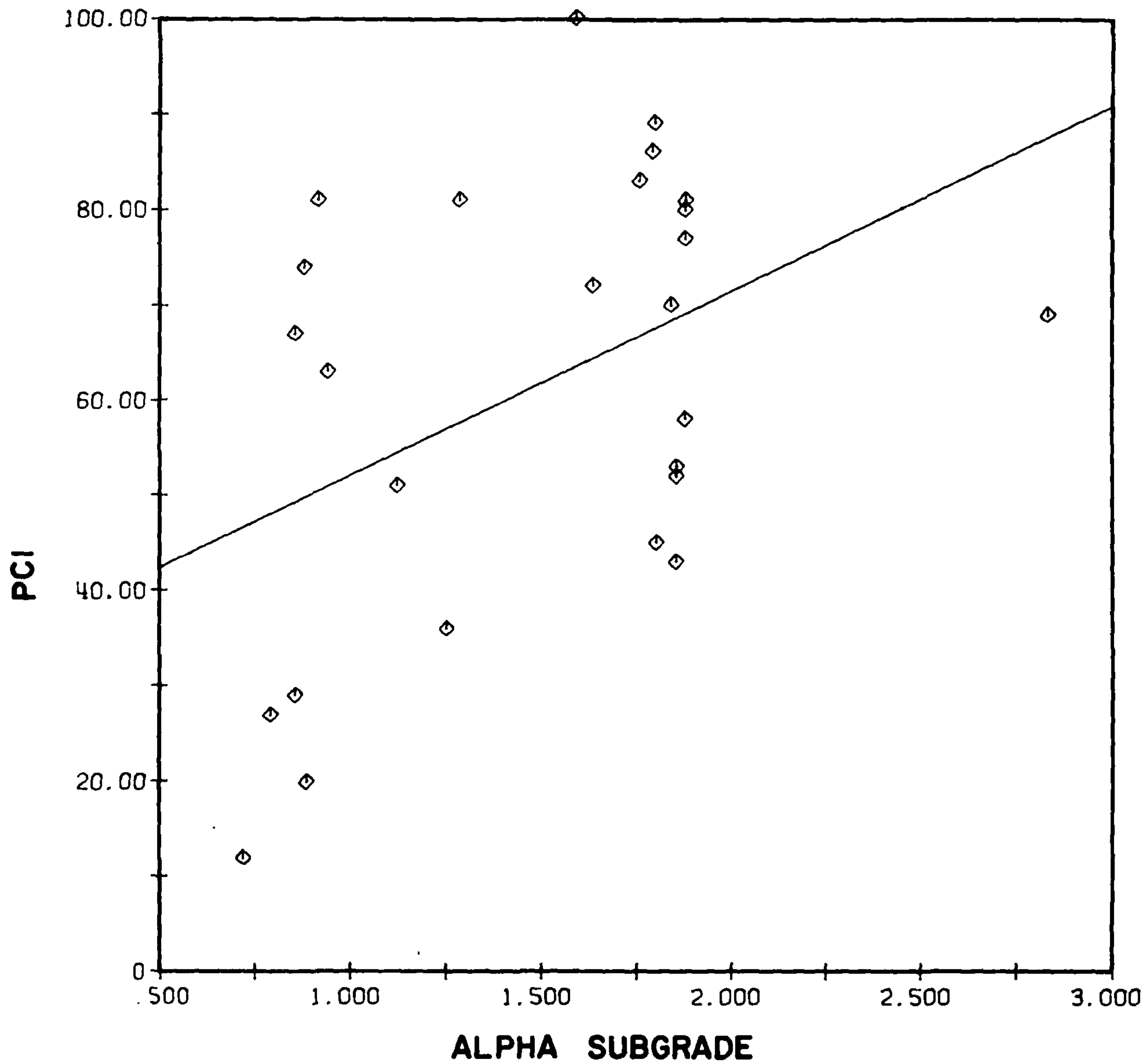

Figure 38. Correlation Between PCI and Load Repetition Factor Computed at the Subgrade Level (α_{SG}) for Asphalt Pavements (No Overlay).

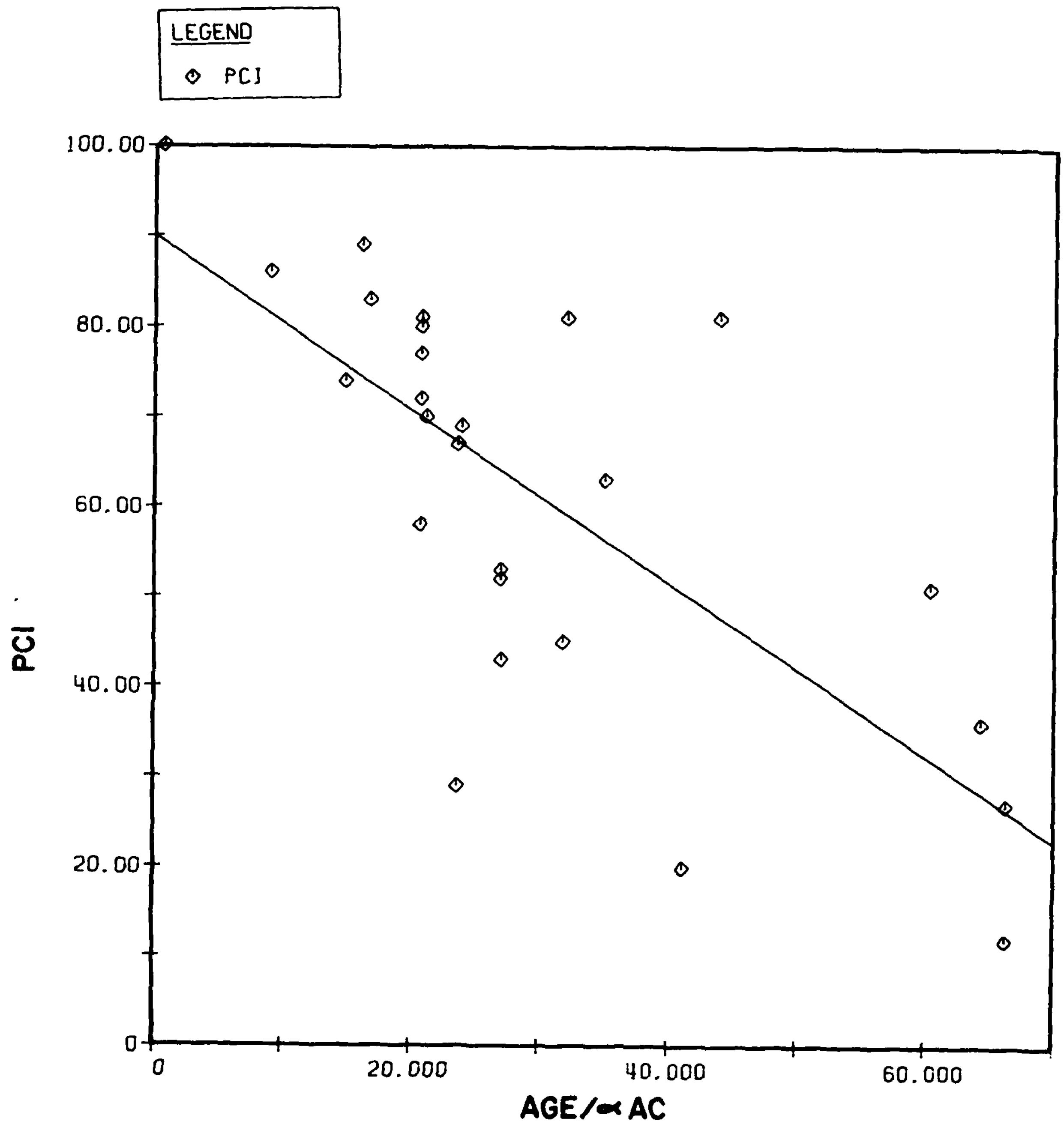

Figure 39. Correlation Between PCI and Age Since Construction Divided by α_{AC} for Asphalt Pavements (No Overlay).

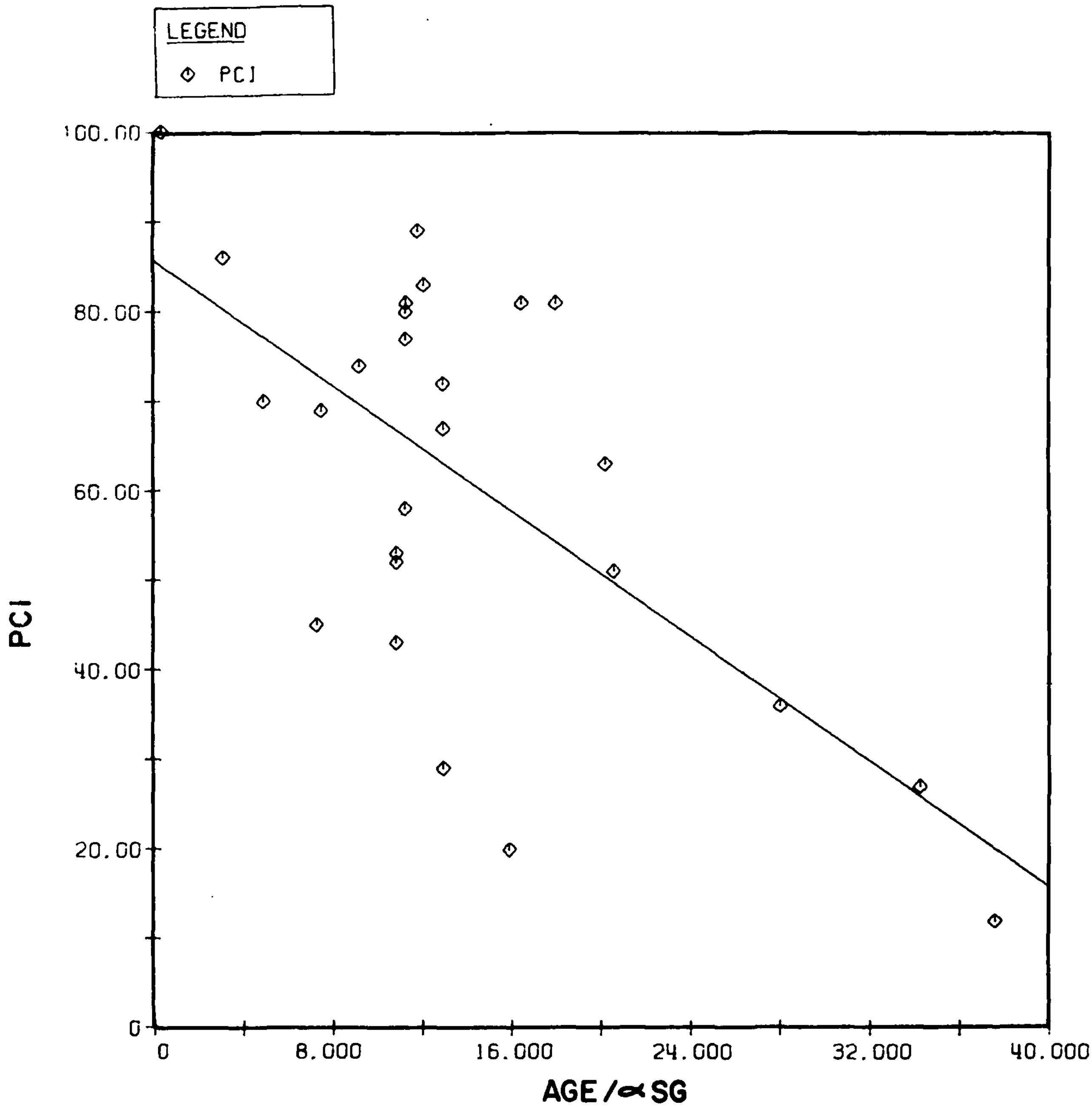

Figure 40. Correlation Between the PCI and Age Since Construction Divided by α_{SG} for Asphalt Pavements (No Overlay).

Table 21 provides output obtained from the stepwise regression analysis, and gives the R^2 and standard deviation of residuals associated with each step. The steps listed in Table 21 provide that each variable included is significant to at least 0.05 level (using the F-test). The model obtained in Step 3 is presented and discussed below:

$$PCI = 100 - AGEOR\left[\frac{1.562}{\alpha_{AC}} - 0.5607\, t_{AC} + 0.0302\, AAT\right] \qquad \text{[Equation 7]}$$

where: AGEOR = time in years since the original construction.

α_{AC}* = load repetition factor determined at the AC/base interface; α_{AC} is a function of AC thickness, base CBR and the tire contact area and pressure of an equivalent single wheel

t_{AC} = thickness in inches of the AC surface layer

AAT = annual average temperature (^{o}F).

Figure 41 compares the measured and predicted PCI using Equation 7. The following evaluates the appropriateness of the coefficients of the variables in the model.

Appropriateness of Variables

The main factors known to affect pavement deterioration include traffic, pavement structure and material properties, climate and previous maintenance.

Traffic load intensity is represented in the model through α_{AC}, which is computed based on the dominant aircraft gear configuration, wheel load, and tire pressure. Traffic volume is considered indirectly through the age variable.

Pavement structure and material properties are represented by the variables α_{AC} and t_{AC}. The surface thickness (t_{AC}) is included in the model as an independent variable and also as one of the data items needed to compute α_{AC}. Another material property needed to compute α_{AC} is the base CBR. The effect of subgrade quality (foundation support) is not represented in the model. It is believed that pavement structure and material properties will be better represented when more data are available. For future development, it is also recommended that stresses and strains computed from pavement mechanistic models (such as the layer program) be included as independent variables.

Climate is represented by the annual average temperature (AAT). Previous maintenance is not represented in the model. The only maintenance-related variable included in the development was percent patching by area; however, its effect within the limited data was not significant enough to be included in the model.

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* See Section II for an explanation of the detailed procedure to compute α_{AC}.

TABLE 21. COEFFICIENT FOR FLEXIBLE PAVEMENT, ORIGINAL CONSTRUCTION PCI PREDICTION MODEL (NO OVERLAY)

Variables	Step No. 1	2	3
Constant	100	100	100
Age Since Construction/α_{AC}	-1.208	-1.705	-1.562
Age Since Construction x t	0	0.2205	0.5607
Age Since Construction x AAT	0	0	-0.0302
R^{2*}	0.475	0.479	0.777
SD^{**}	16.79	15.34	11.4

where: Age = Time in Years Since Original Construction

α_{AC} = Load Repetition Factor or AC, Base Interface

t_{AC} = Thickness of AC (Inches)

AAT = Annual Average Temperature (^{o}F).

* R^2 = Proportion of Total Variation About the Mean PCI of All Data Explained by the Regression

** SD = Standard Deviation of the Residual (PCI_{actual} - $PCI_{predicted}$).

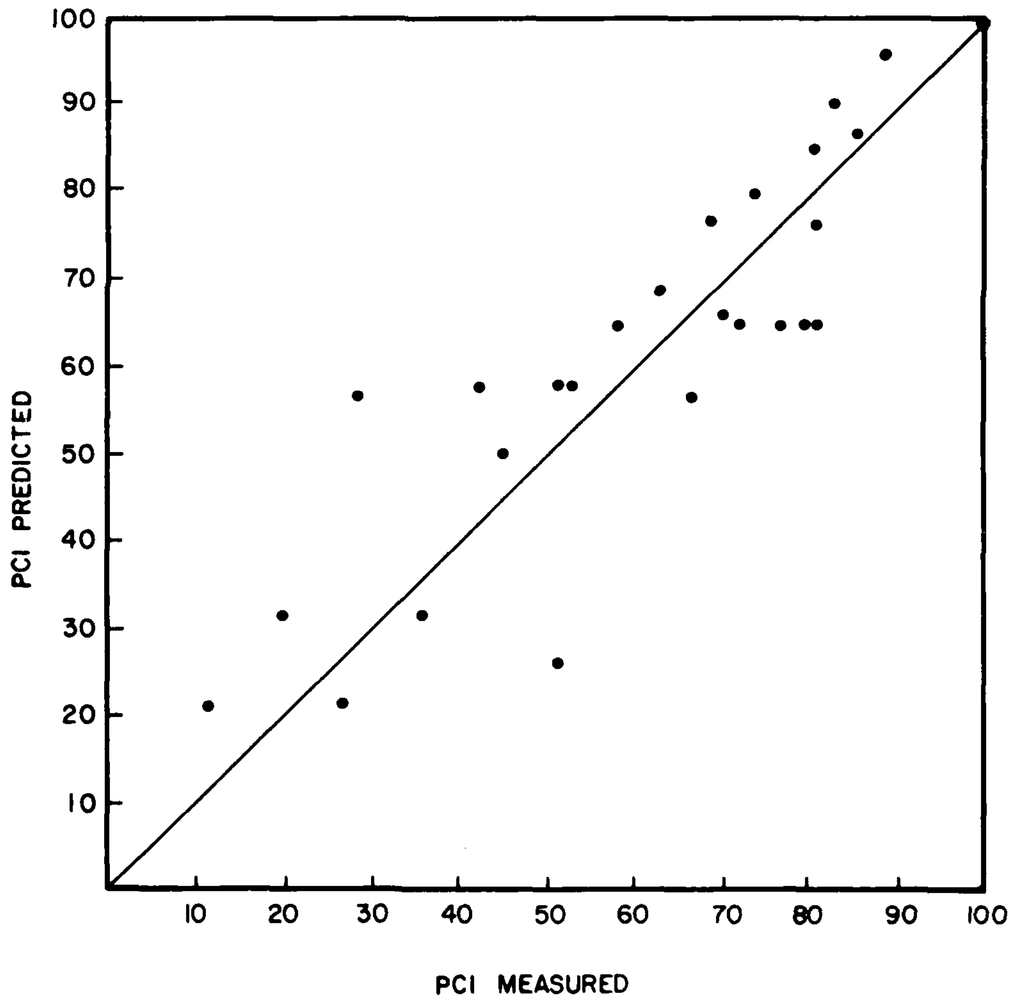

Figure 41. Comparison Between PCI Measured and PCI Predicted (No Overlay).

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Coefficients of Variables

Because of the intercorrelation of the variables, the coefficient of each independent variable does not represent the exact influence that each variable has on the PCI. For example, in Equation 7, the negative coefficient for age since construction x $1/\alpha_{AC}$ is explainable; both age and $1/\alpha_{AC}$ are negatively correlated with the PCI, so their interaction has a negative effect on the PCI. The coefficient of the second variable (age x AC thickness) has a positive sign. This cannot be readily explained for two reasons: (1) the age is negatively correlated with the PCI, and the AC thickness is positively correlated with the PCI, and (2) the AC thickness is one of the factors needed to compute α_{AC}, which has already appeared in the equation. When changing the AC thickness in the model, the user should look for an increase or decrease in the PCI. If the result opposes the acceptable engineering insight, the model should be further investigated for errors and possible lack of data.

Table 21 shows significant increase in R^2 and the reduction in the standard deviation when the variable age x AAT has entered the equation (Step 3). Figure 42 is a graph illustrating the interaction effect between age and temperature on the PCI. For the data included in this analysis, the following can be concluded: (1) the rate of PCI decrease with age is much higher for AAT below 60^oF than for AAT above 60^oF, and (2) for a given rate of PCI decrease with age (i.e., above or below 60^oF), the higher the temperature, the lower the PCI at any specific age. These conclusions are limited to the available data and cannot be generalized before more data are obtained and the interactions of other environmental variables (such as precipitation) with age and temperature are examined.

Generally, the larger the data base, the more useful the regression model; it is wise to restrict the use of the prediction regression model to the region of the "X-space" from which the original data were obtained (Reference 12). In Equation 7, the original data and the space (range) associated with each of them is:

Variable	Mean	Range (space)
AC thickness (inches)	3.9	2 to 7.5
Base CBR (percent)	71	24 to 100
Aircraft	--	T-37, T-38, F-4, DC-9, C-130, C-141, and B-52
AAT (^oF)	59	31 to 75
Age since original construction (years)	18	0.5 to 35
PCI	61	12 to 100

Use of the equation should be limited to the ranges shown above; furthermore, it is less hazardous to use the equation only in the region of the "X-Space" that covers the interaction of ranges for all the variables. This is particularly true if the variables are highly correlated. For example, by examining the correlation matrix (Table 20), the only significant correlation

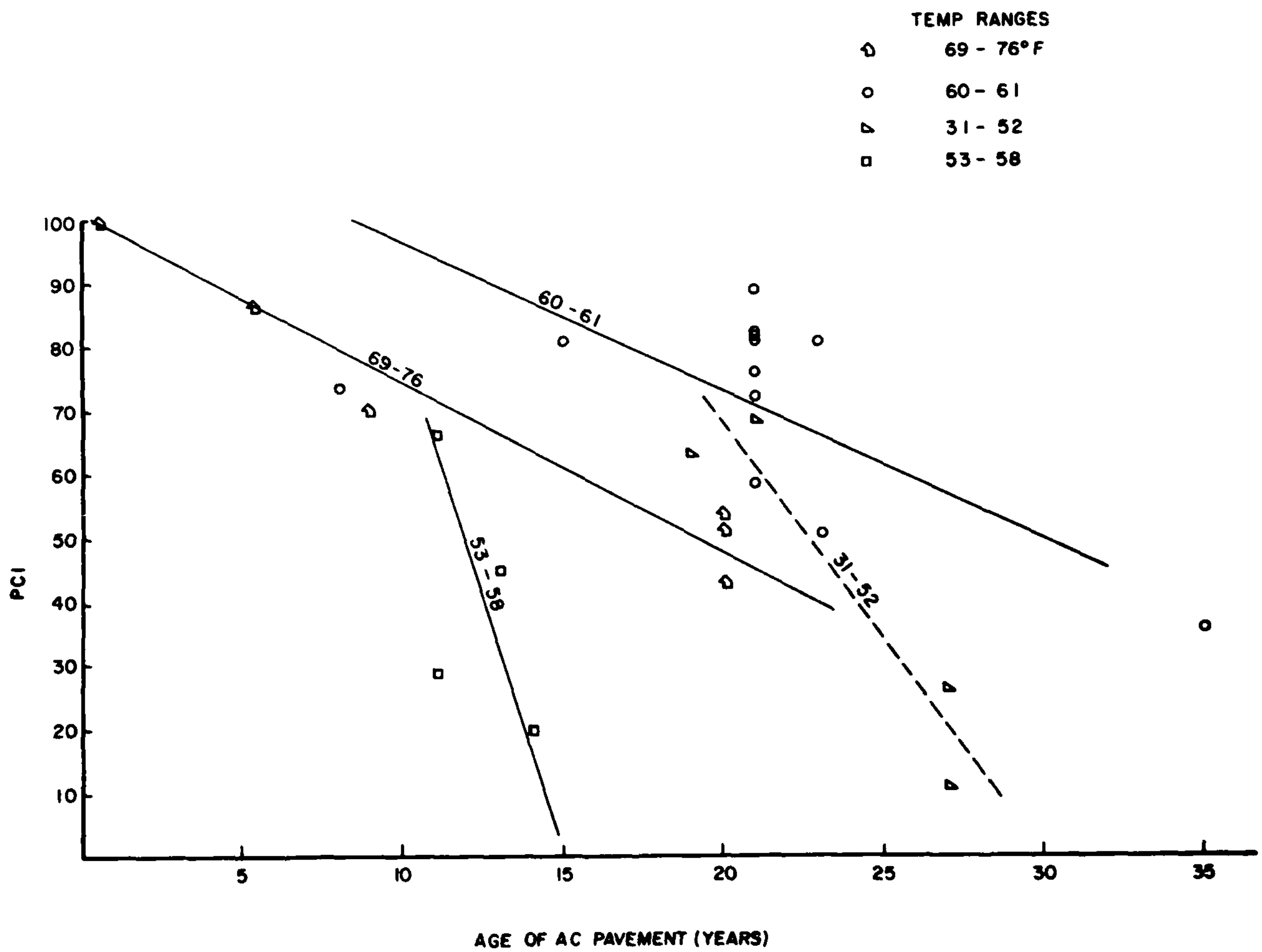

Figure 42. Interaction Effect Between Age of AC Pavement (Years) and Temperature.

between the independent variables is found between AC thickness and Base CBR. Figure 43 is a plot of this correlation. As shown, the "X-Space" covering the ranges of the two variables is smaller than the individual ranges. Therefore, predicting the PCI where Base CBR is 25 and AC thickness is 2 inches is rather dangerous, since this point lies outside the space from which data were collected. Of course, when more variables that are highly correlated are involved in the prediction model, identifying the rather safe "X-Space" becomes more difficult. This problem can be minimized by increasing the volume of data and by covering as large a space of the variable interactions as is practically feasible during the model development. In addition, the engineer should limit use of the model to the conditions from which the data were collected, rather than using it for hypothetical conditions.

The recommendations provided above apply in concept to all models discussed in the remainder of this section.

PCI PREDICTION -- AC OVERLAY MODEL

The method for developing the PCI prediction model for AC overlay is the same as described for the original construction (nonoverlay) model. The independent variables used in the stepwise regression program are listed in Part B of Table 19. The usable data were taken from 11 pavement features (Appendix B). Table 22 shows the correlation matrix, including the PCI and independent variables. Figures 44 and 45 are plots of variables having the highest correlation with the PCI. When the model was developed, the independent variables were introduced to interact with age since the last overlay. This interaction insures that immediately after the overlay, the PCI would be 100. Figure 46 is an example correlation plot of an independent variable interacted with age since last overlay and the PCI.

Table 22 shows the output obtained from the stepwise regression analysis. The steps listed in Table 23 provide that each variable included is significant to at least the 0.05 level (using the F-test). The model obtained in Step 2 is discussed below:

$$PCI = 100 - AGEOL \left[\frac{3.775}{\alpha_{SG}} + 0.00598\ ACWGT\right] \qquad \text{[Equation 8]}$$

where: AGEOL = age in years since last overlay

α_{SG} = load repetition factor determined at the subgrade level;* α_{SG} is a function of total pavement thickness above the subgrade, subgrade CBR, and the tire contact area and tire pressure of an equivalent single-wheel

ACWGT = maximum gross aircraft weight (kips).

* Section II provides the detailed procedure for computing α_{SG}.

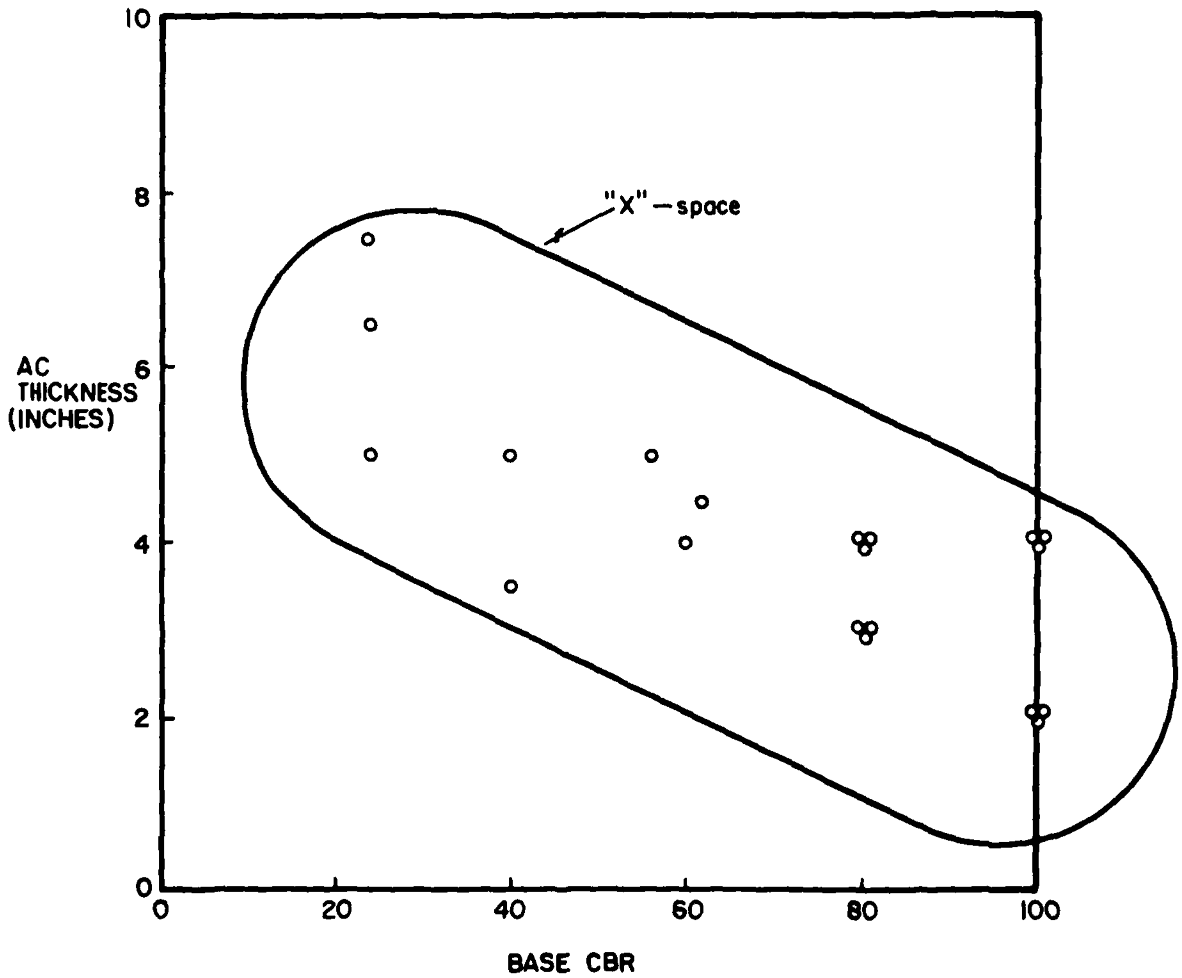

Figure 43. Correlation Between Base CBR and AC Thickness for Asphalt Pavement Features (No Overlay).

TABLE 22. CORRELATION MATRIX FOR ASPHALT PAVEMENT (OVERLAY)

	Age	Age OROL	T AC THICK	ACOL THICK	B THICK	SB THICK	B CBR	SB CBR	SG CBR	ACWGT	AREA	P/S	FEAT	FI	PRECI	AA TEMP	ADTR	AATR	σ_{AC}	σ_{SG}	T Equiv Thick	a Equiv Thick	TA	PATCH	PCI
Age	1.0	-.20	-.50	.59	-.31	-.21	-.02	-.15	.17	-.24	.15	.93	-.56	.09	.14	-.05	-.24	-.07	-.50	-.04	-.41	-.01	.89	.43	-.79
Age OROL		1.0	.28	.29	.64	-.48	-.71	-.71	.46	.32	.56	-.43	.61	.19	.39	-.05	-.53	-.14	-.38	-.06	-.24	-.01	-.31	-.56	.09
T AC THICK			1.0	.38	.21	.17	-.26	-.21	.06	.42	.01	-.54	.55	.16	-.05	-.23	-.04	.30	.47	.06	.48	.07	-.56	-.42	.28
ACOL THICK				1.0	.16	.60	-.05	.13	-.32	.52	-.12	-.53	.34	-.33	.06	.24	.10	-.19	.08	.02	.72	-.02	-.49	-.44	.43
B THICK					1.0	-.40	-.25	-.39	.24	.13	.28	-.40	.41	.09	.28	.01	-.35	-.12	.05	.05	-.09	.08	-.39	-.42	.37
SB THICK						1.0	.61	.72	-.37	.38	-.47	0	-.21	-.21	-.28	-.04	.39	.22	.41	.32	.92	.25	-.18	-.14	.30
B CBR							1.0	.91	-.24	-.08	-.53	.27	-.46	-.10	-.17	-.13	.20	.35	.59	.42	.47	.36	-.03	-.06	.41
SB CBR								1.0	-.42	-.22	-.36	.14	-.25	-.33	-.17	.11	.34	.15	.64	.51	.54	.45	-.09	-.03	.46
SG CBR									1.0	.43	.45	-.09	.19	.91	-.33	-.82	-.10	.65	-.25	.36	-.30	.43	-.17	-.30	-.06
ACWGT										1.0	-.23	-.31	.02	.56	-.34	-.64	.06	.57	-.15	-.01	.52	0	-.41	-.43	.12
AREA											1.0	-.12	.67	.10	.18	.05	-.22	-.19	-.22	.44	-.41	.48	-.03	-.22	-.02
P/S												1.0	-.70	-.11	.24	.07	-.27	-.09	-.30	-.07	-.24	-.07	.88	.40	-.64
FEAT													1.0	-.02	.18	.08	-.16	-.09	.23	.29	.02	.32	.64	-.57	.52
FI														1.0	-.57	-.96	.12	.84	-.13	.21	-.14	.26	-.22	-.15	-.07
PRECI															1.0	.56	-.88	-.56	-.10	-.24	-.20	-.23	.23	-.37	.02
AA TEMP																1.0	-.12	-.95	-.06	-.30	-.10	-.34	.27	.26	-.05
ADTR																	1.0	.17	.17	.17	.26	.13	-.17	.54	.01
AATR																		1.0	.32	.39	.27	.41	-.35	-.31	.21
σ_{AC}																			1.0	.49	.53	.46	-.49	-.28	.66
σ_{SG}																				1.0	.31	1.0	-.27	-.36	.42
T Equiv Thick																					1.0	.25	-.41	-.35	.45
a Equiv Thick																						1.0	-.26	-.37	.40
TA																							1.0	.61	-.83
PATCH																								1.0	-.68
PCI																									1.0

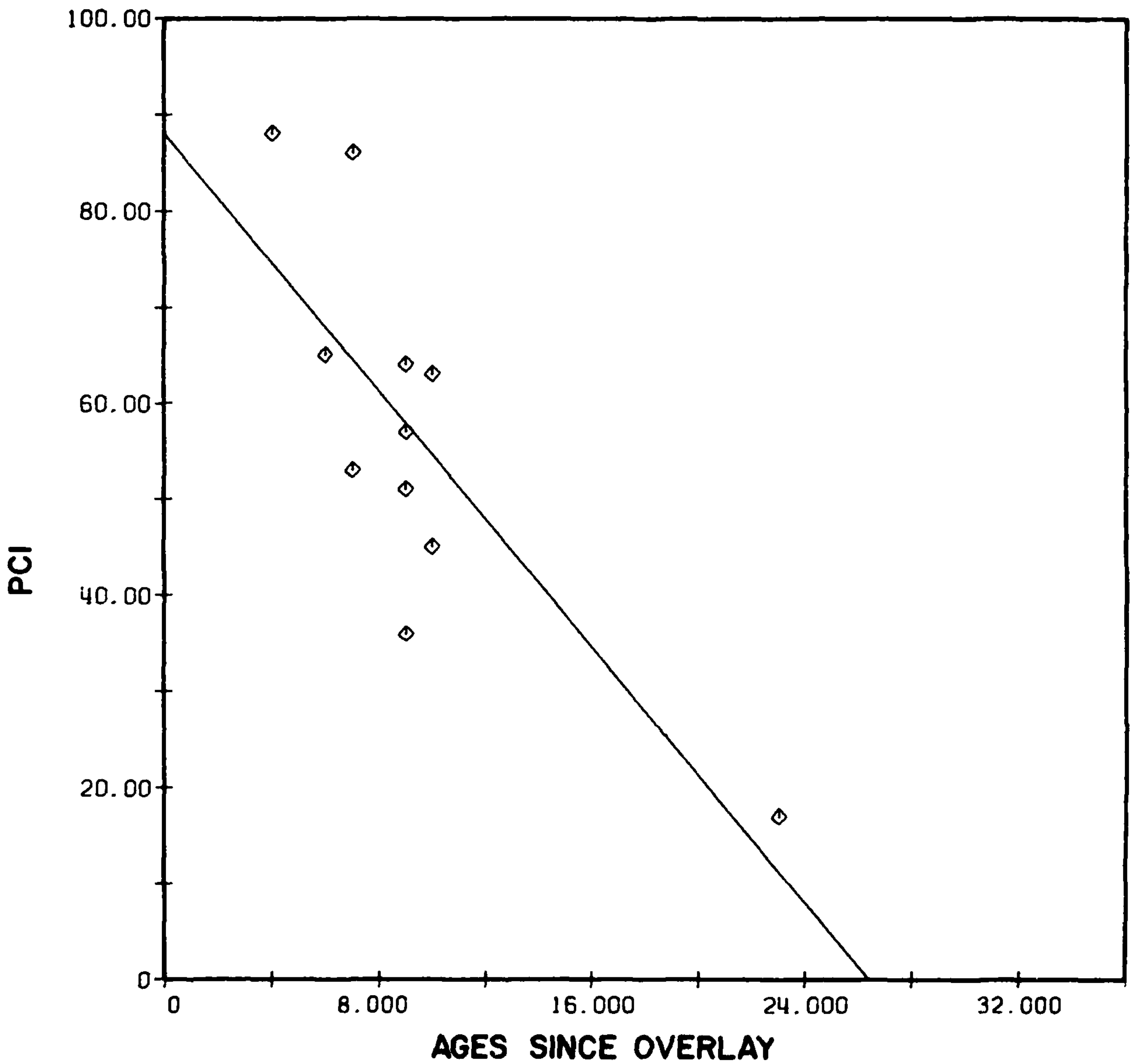

Figure 44. Correlation Between the PCI and Age Since Overlay.

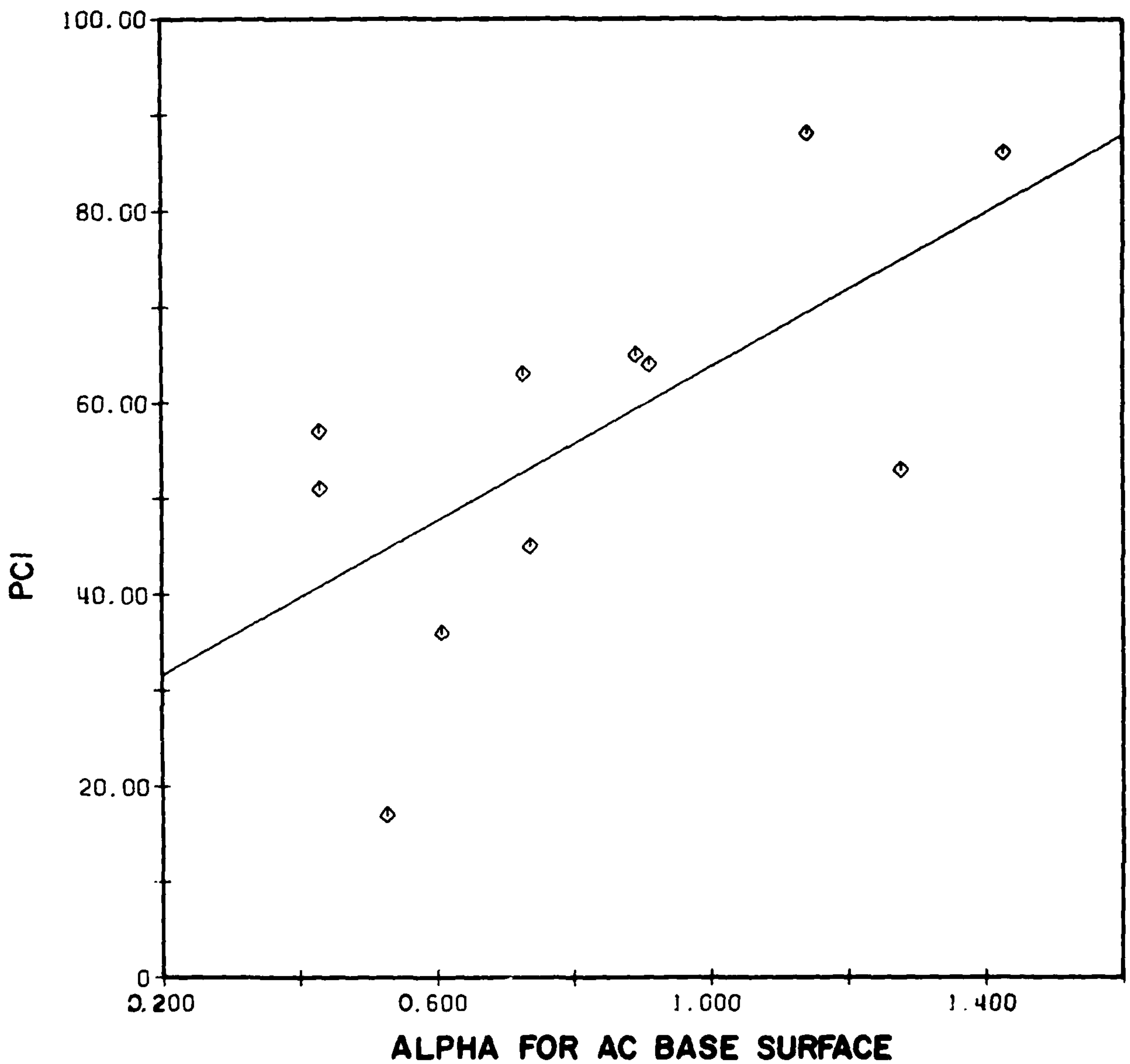

Figure 45. Correlation Between the PCI and α_{AC} for Asphalt Pavements That Have Been Overlaid.

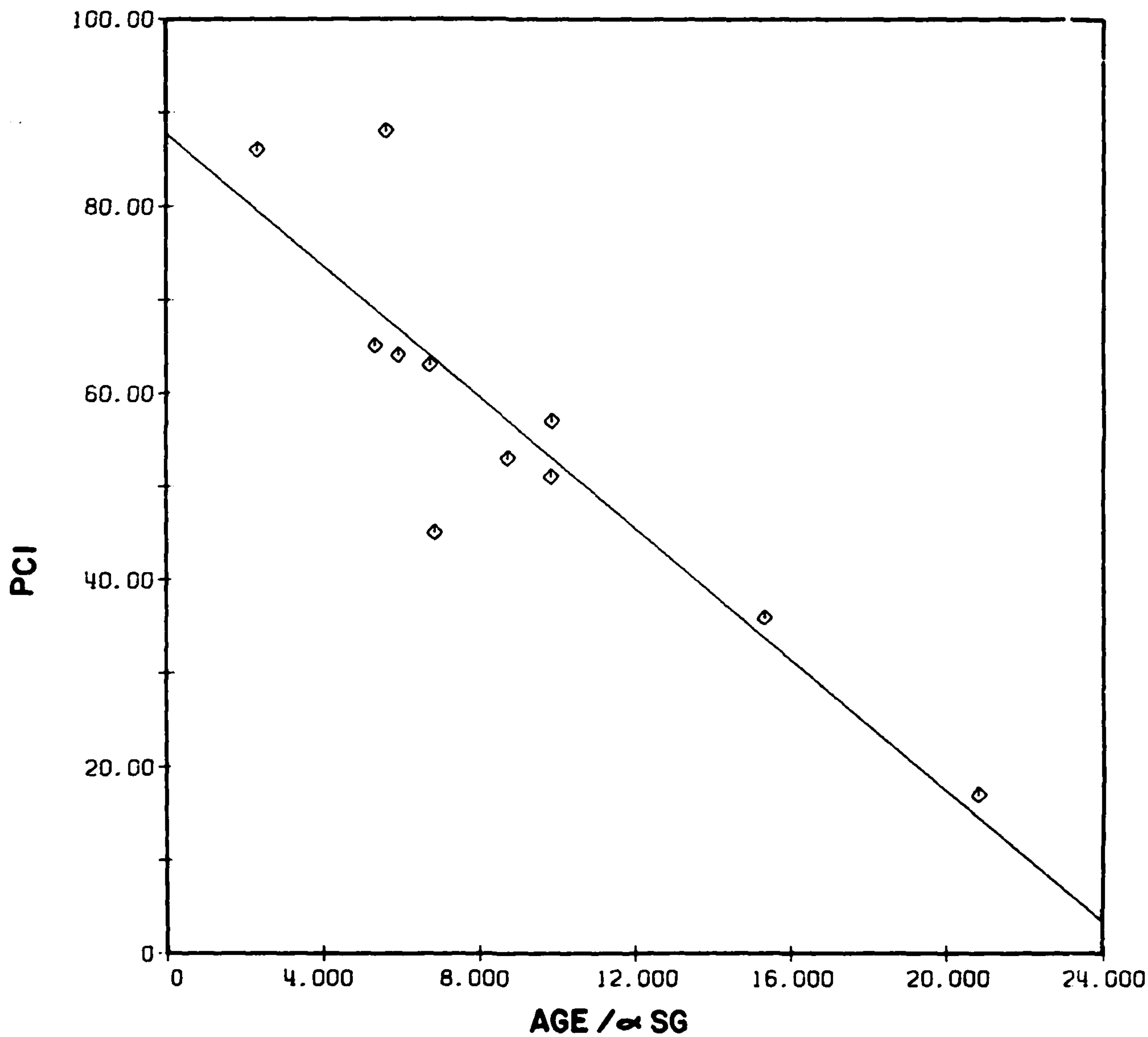

Figure 46. Correlation Between the PCI and Age Since Overlay Divided by α_{SG}.

TABLE 23. COEFFICIENTS FOR FLEXIBLE PAVEMENT, ASPHALT CONCRETE OVERLAY PCI PREDICTION MODELS

Variables	Step No. 1	Step No. 2
Constant	100	100
Age Since Last Overlay/α_{SG}	-4.56	-3.775
Age Since Last Overlay x ACWGT	0	-0.00598
R^2	0.7	0.89
SD	11.2	7.1

Figure 47 compares the measured and the predicted PCI using Equation 8. Following is an evaluation of the model.

Appropriateness of Variables

Traffic load intensity is well represented in the model by α_{SG} and ACWGT. Accumulated traffic loading is indirectly considered through the age factor.

Pavement structure is represented only through the total pavement thickness above the subgrade and the subgrade CBR, since both of these factors are used to compute α_{SG}. Material properties of the different layers above the subgrade, climate, and previous localized maintenance are not represented in the model. However, since there are only 11 data points, not many variables could have been included without loss of significance of the model.

Coefficients of Variables

The model's variable coefficient signs are easily explained. As the subgrade CBR and/or pavement thickness increase, the α_{SG} increases, which causes the PCI to be higher. The sign for ACWGT indicates that as the aircraft weight increases, the PCI decreases.

No firm conclusions can be based on the 11 data points. However, considering that the data came from seven different airfields and that R^2 of 0.7 was achieved in Step 1, the decrease in PCI with age of AC overlays seems to be quite predictable. The range of values used to develop Equation 8 is presented below:

Variable	Mean	Range
Age since last overlay (years)	9.4	4-23
Subgrade CBR (percent)	20.3	5-50
Pavement thickness above subgrade (inches)	23.1	14-57
Aircraft	--	F-4, DC-9, C-130, B-707, and B-52

The use of Equation 8 should be limited to the ranges listed above, and preferably only to the "X-Space" that covers the interaction between the ranges as previously discussed for Equation 7.

PCI PREDICTION -- COMBINED MODEL

The development of this model was based on 37 data points: 26 were from AC pavements that had not received any AC overlays, and 11 were from AC pavements that had received AC overlays. The independent variables used in the stepwise regression were a combination of those used in each of the cases shown in Table 19. Table 24 shows the correlation matrix, which includes the PCI and independent variables. Figures 48 and 49 are plots of variables

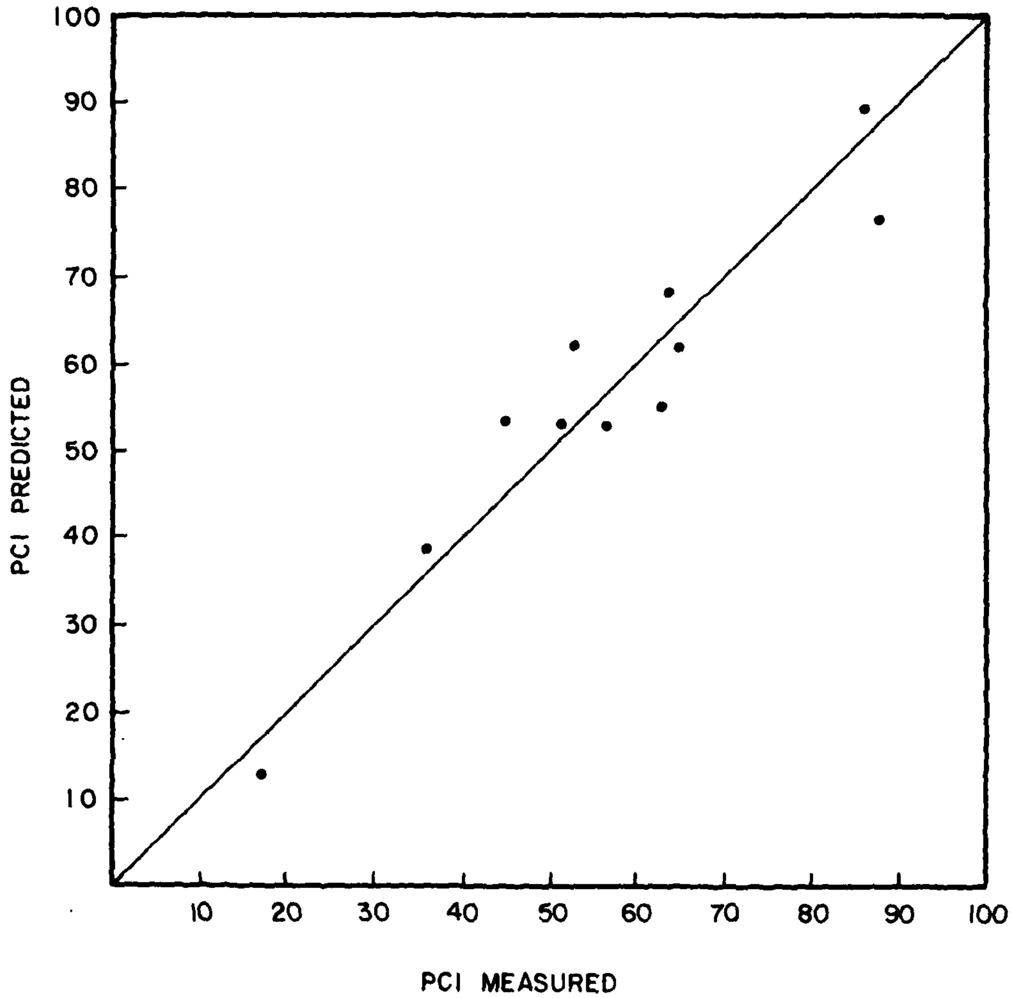

Figure 47. Comparison Between PCI Measured and PCI Predicted (Overlay AC Pavement).

TABLE 24. CORRELATION MATRIX FOR ASPHALT PAVEMENTS (WITH AND WITHOUT OVERLAY)

	Age	Age OROL	T AC THICK	ACOL THICK	B THICK	SB THICK	B CBR	SB CBR	SG CBR	ACWGT	AREA	P/S
Age	1.0	-.51	-.33	-.54	.10	-.08	-.03	-.20	.18	.02	-.44	.21
Age OROL		1.0	.67	.87	-.07	-.15	-.38	-.11	.02	.20	.16	-.21
T AC THICK			1.0	.68	-.04	-.11	-.54	-.17	.08	.26	.11	-.31
ACOL THICK				1.0	-.10	.15	-.25	.06	-.09	.26	.03	-.25
B THICK					1.0	.10	-.06	-.16	-.23	.29	.16	-.26
SB THICK						1.0	.54	.66	-.48	.41	-.34	-.08
B CBR							1.0	.64	-.06	-.07	-.42	.09
SB CBR								1.0	-.41	-.06	-.20	-.15
SG CBR									1.0	.04	.01	.28
ACWGT										1.0	-.19	-.13
AREA											1.0	-.03
P/S												1.0

	FEAT	FI	PRECI	AA TEMP	ADTR	AATR	σ_{AC}	σ_{SG}	T Equiv Thick	α Equiv Thick	TA	PATCH	PCI
Age	-.42	-.12	.29	.04	-.43	-.06	-.16	.10	-.11	.12	.26	-.08	-.34
Age OROL	.29	.38	.01	-.36	-.01	.19	.12	-.20	-.04	-.23	-.08	.21	-.08
T AC THICK	.44	.30	.01	-.29	-.01	.13	.27	.13	.10	-.14	-.25	.01	.12
ACOL THICK	.26	.16	-.04	-.25	.07	.15	.20	-.16	.21	-.22	-.13	.13	.32
B THICK	.31	-.04	-.01	-.06	-.01	-.06	-.05	-.11	.49	-.17	.03	-.13	.06
SB THICK	-.05	-.12	-.39	-.24	.42	.35	.04	.01	.88	-.14	.36	-.07	-.10
B CBR	-.44	-.10	-.18	-.04	.07	.19	.27	.29	.37	.28	.17	-.12	.04
SB CBR	.06	-.17	-.40	-.10	.47	.34	.38	.40	.49	.27	.09	.03	.22
SG CBR	-.32	.34	.39	.06	-.52	-.33	-.14	.23	-.47	.40	-.17	-.12	-.18
ACWGT	.23	.46	-.14	-.64	-.03	.29	-.47	-.48	.55	-.54	.46	-.08	-.46
AREA	.62	-.03	.10	.25	.16	-.26	-.18	.11	-.20	.12	-.21	-.04	.25
P/S	-.48	-.13	.32	.27	-.17	-.44	-.31	-.03	-.26	.02	.06	.08	-.36
FEAT	1.0	.07	-.16	-.17	.28	.10	-.06	-.09	.18	-.18	-.10	-.13	.25
FI		1.0	-.38	-.82	.01	.54	-.07	0.02	-.05	-.03	-.01	.02	-.14
PRECI			1.0	.41	-.81	-.50	-.14	-.12	-.34	-.02	.03	-.21	-.23
AA TEMP				1.0	.39	-.05	-.07	.11	-.10	.07	-.09	-.07	.20
ADTR					1.0	.22	.03	.10	.35	0	0	.21	.24
AATR						1.0	.22	.05	.30	-.09	.15	-.07	.02
σ_{AC}							1.0	.52	.09	.52	-.45	-.12	.57
σ_{SG}								1.0	-.07	.95	-.41	-.28	.43
T Equiv Thick									1.0	-.21	.28	-.12	-.03
α Equiv Thick										1.0	-.45	-.30	.44
TA											1.0	.21	-.77
PATCH												1.0	-.18
PCI													1.0

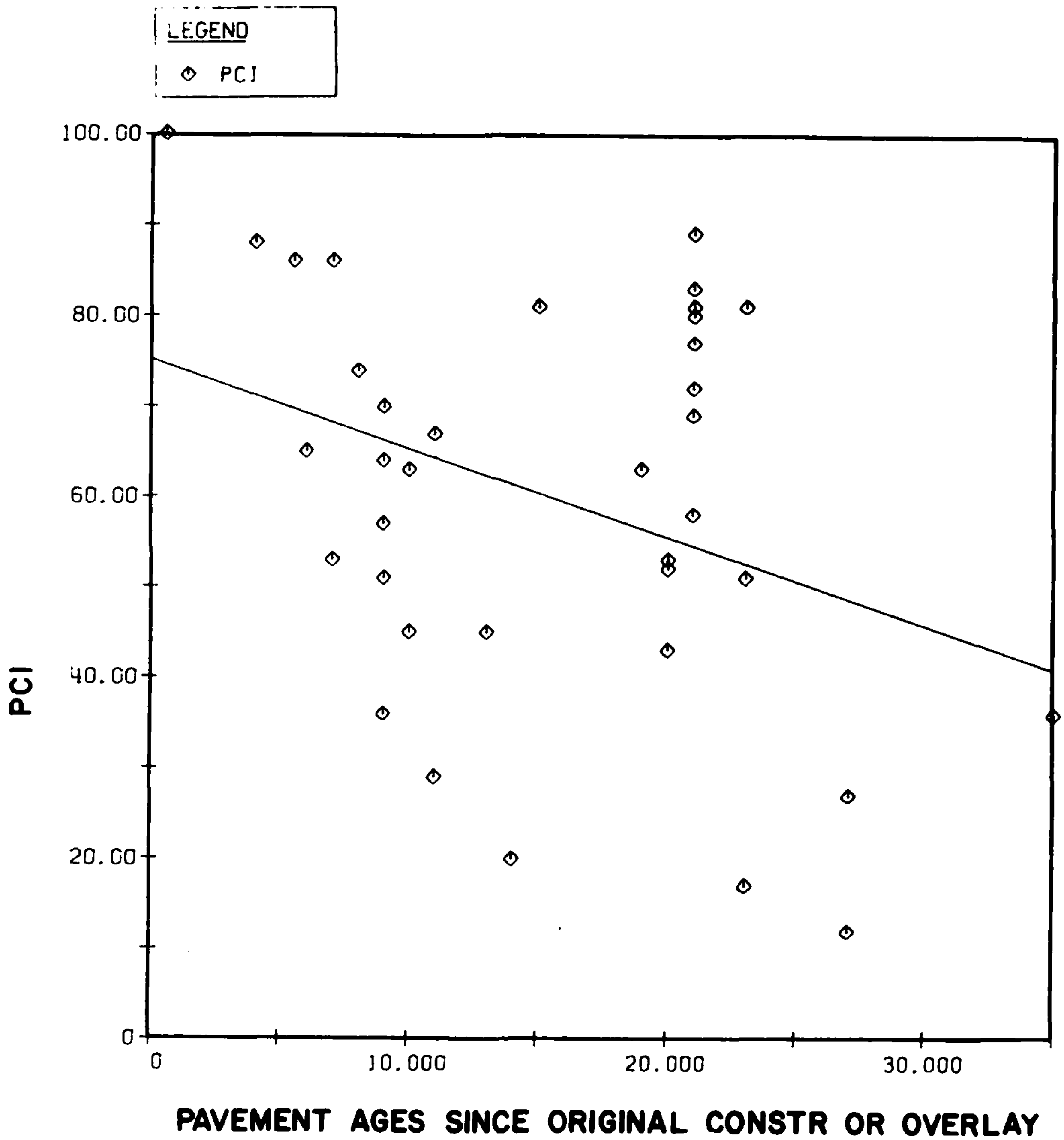

Figure 48. Correlation Between PCI and Ages Since Original Construction or Overlays for Asphalt Pavements (Overlay and No Overlay Data).

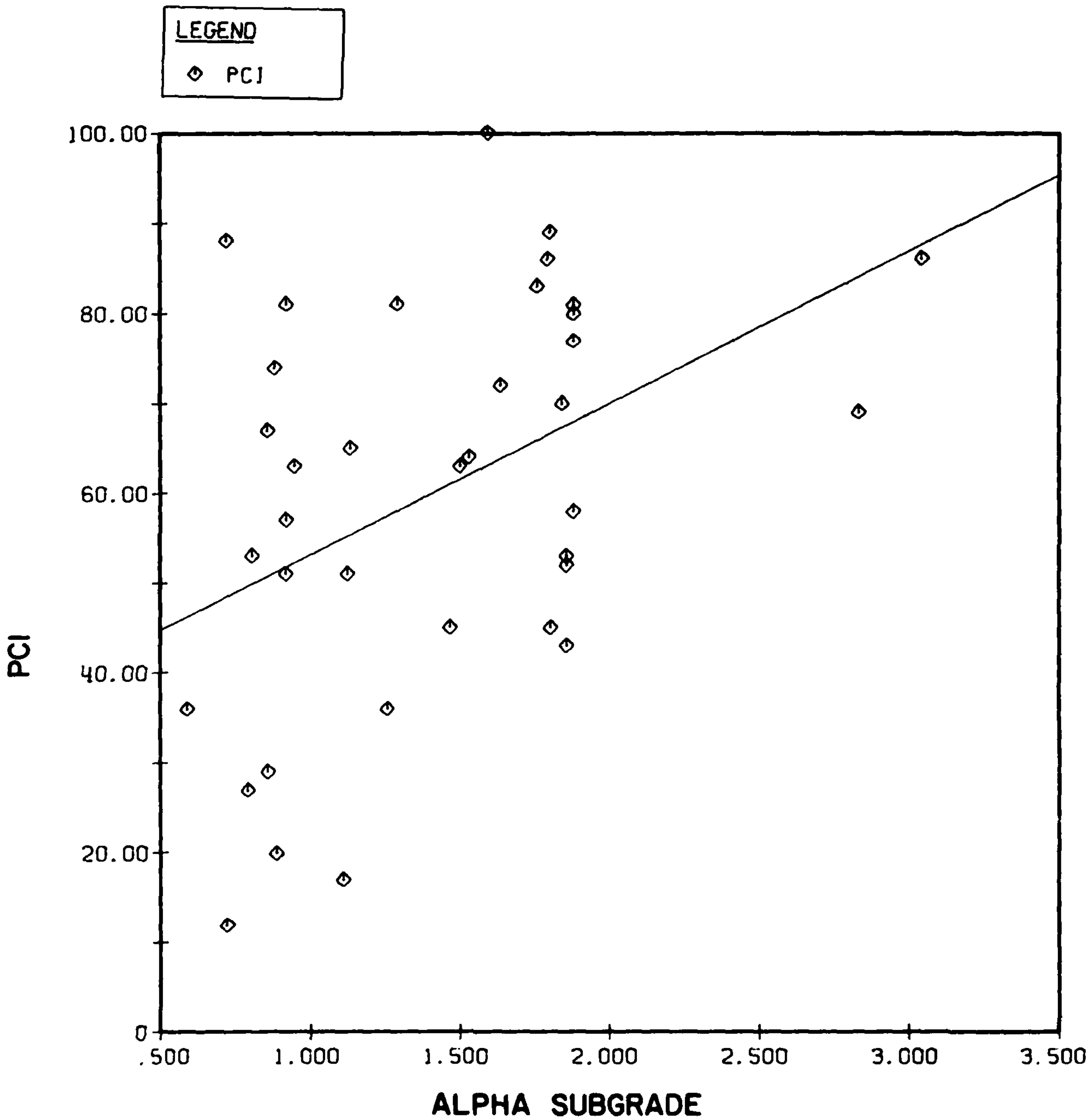

Figure 49. Correlation Between the PCI and Load Repetition Factor Computed at the Subgrade Level of (α_{SG}) for Asphalt Pavement (Overlay and No Overlay Data).

having the highest correlation with the PCI. In developing the models, all variables were interacted with age since construction or last overlay (if pavement is overlaid) to insure that at age equal to zero, the PCI is equal to 100.

Figures 50, 51, and 52 are correlation plots of variables interacted with age and the PCI.

Table 25 presents the output obtained from the stepwise regression analysis. The steps listed in the table provide that each variable included is significant to at least the 0.05 level (using the F-test). The model obtained in Step 4 is presented in Equation 9.

$$PCI = 100 - AGE\left[\frac{1.487}{\alpha_{SG}} + 0.143 \times AGECOL + \frac{6.56}{T_{AC}} - 1.23\ \alpha_{AC}\right] \qquad \text{[Equation 9]}$$

where: AGE = age since original construction or since last overlay if the pavement has been overlaid

α_{SG} = load repetition factor determined at the subgrade level; α_{SG} is a function of total pavement thickness above the subgrade, subgrade CBR, and the tire contact area and tire pressure of an equivalent single wheel

AGECOL = age between the time the pavement was constructed and the time it received the last overlay; equals zero if the pavement was not overlaid

T_{AC} = total AC thickness in inches including overlay, if any

α_{AC} = load repetition factor determined at the AC base.

Figure 53 compares the measured and predicted PCI using the above model. Following is an evaluation of the model.

Appropriateness of Variables

In this model, traffic load intensity is represented by α_{SG} and α_{AC}, and traffic volume is represented by the age factor. Pavement structure and material properties are represented by α_{SG}, α_{AC}, and T_{AC}. In this model, the subgrade and base CBR are included through α_{SG} and α_{AC}, respectively. In the previous models, only one was included at a time (see Equations 7 and 8). Climate and previous maintenance are not represented.

Coefficients of Variables

The signs of all the coefficients agree with engineering experience (see the following).

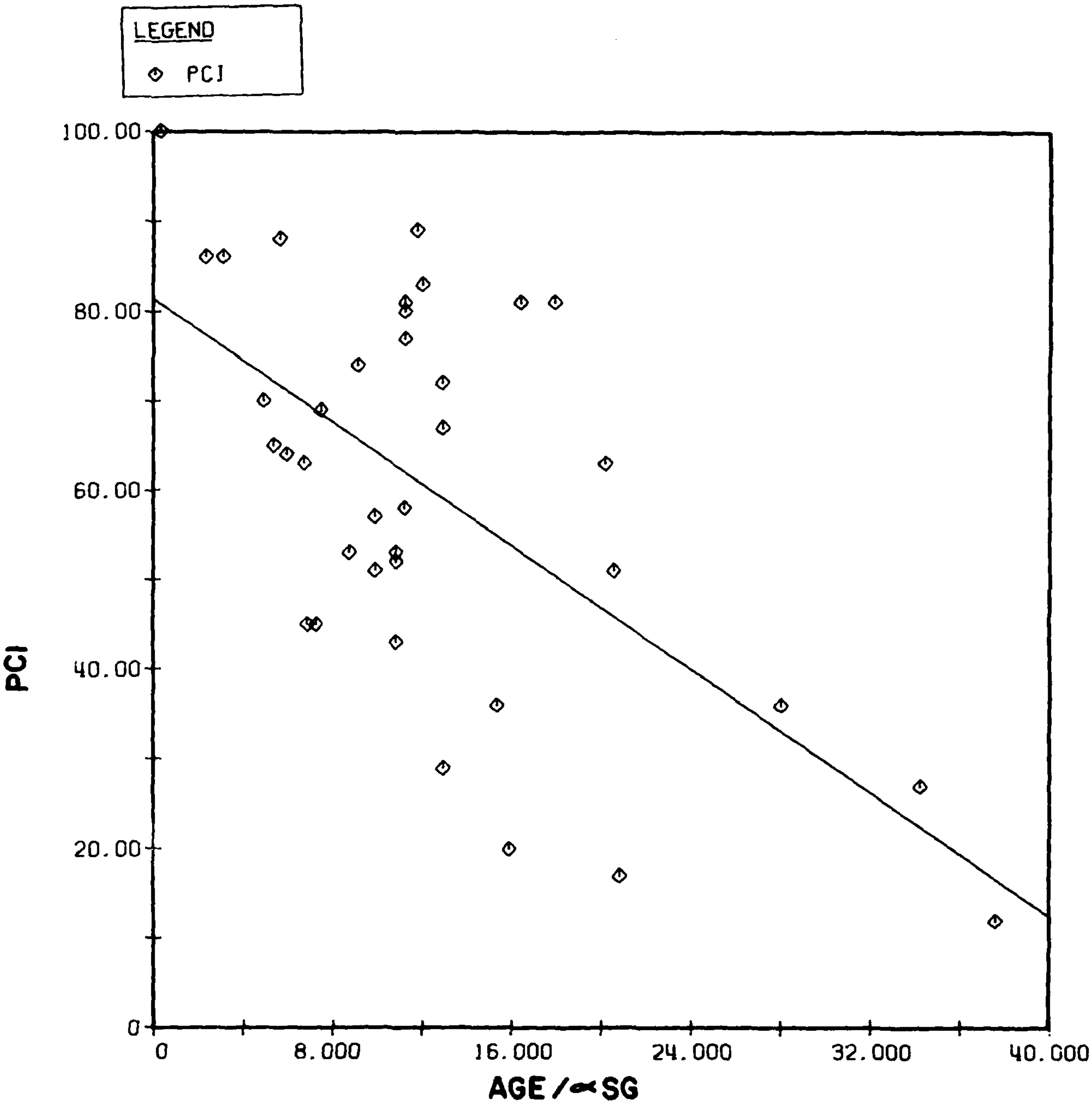

Figure 50. Correlation Between the PCI and Aqe Since Construction or Overlay Divided by α_{SG} for Asphalt Pavement (Overlay and No Overlay Data).

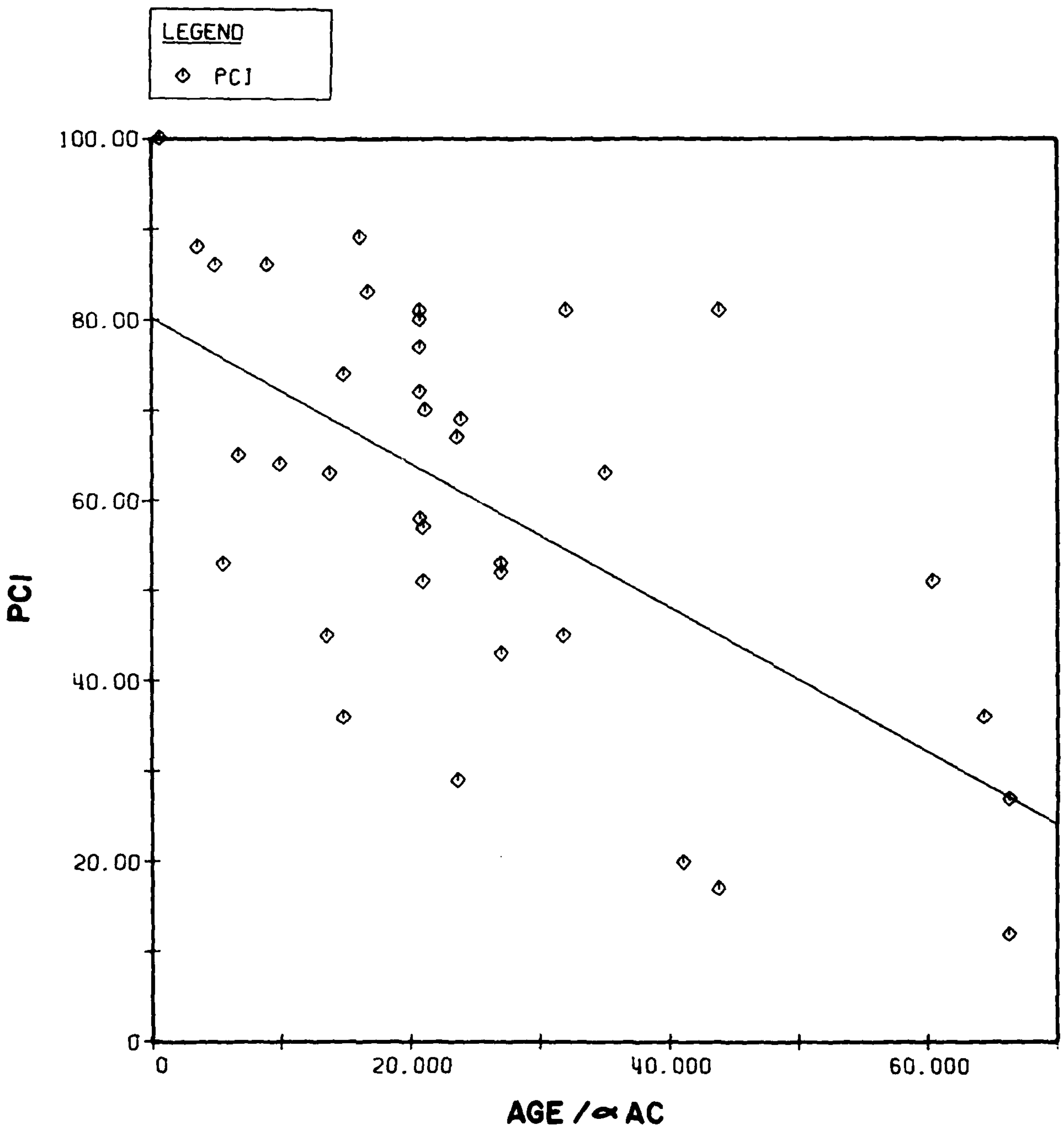

Figure 51. Correlation Between the PCI and Age Since Construction or Overlay Divided by α_{AC} for Asphalt Pavements (Overlay and No Overlay Data).

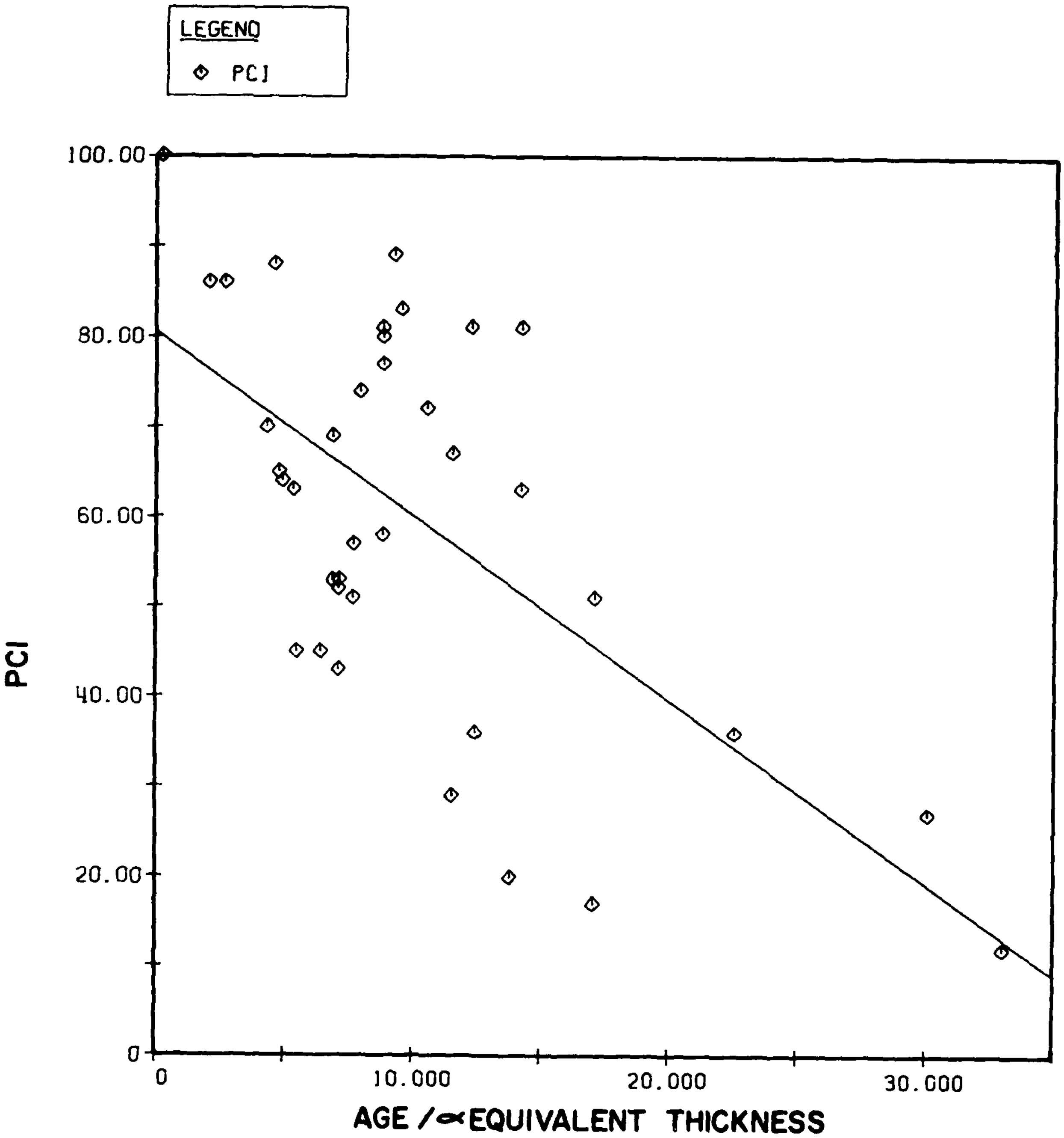

Figure 52. Correlation Between the PCI and Age Since Construction or Overlay Divided by α_{SG} (Based on Equivalent Thickness) for Asphalt Pavement (Overlay and No Overlay Data).

TABLE 25. COEFFICIENTS FOR FLEXIBLE PAVEMENT, COMBINED PCI PREDICTION MODEL

Variables	Step No. 1	2	3	4
Constant	100	100	100	100
Age/α_{SG}	-2.784	-2.511	-1.688	1.487
Age x Age Before Overlay	0	-0.120	-0.129	-0.143
Age/Total AC Thickness	0	0	-2.889	-6.560
Age x α_{AC}	0	0	0	+1.23
R^2	0.18	0.44	0.52	0.62
SD	20.14	16.84	15.89	14.4

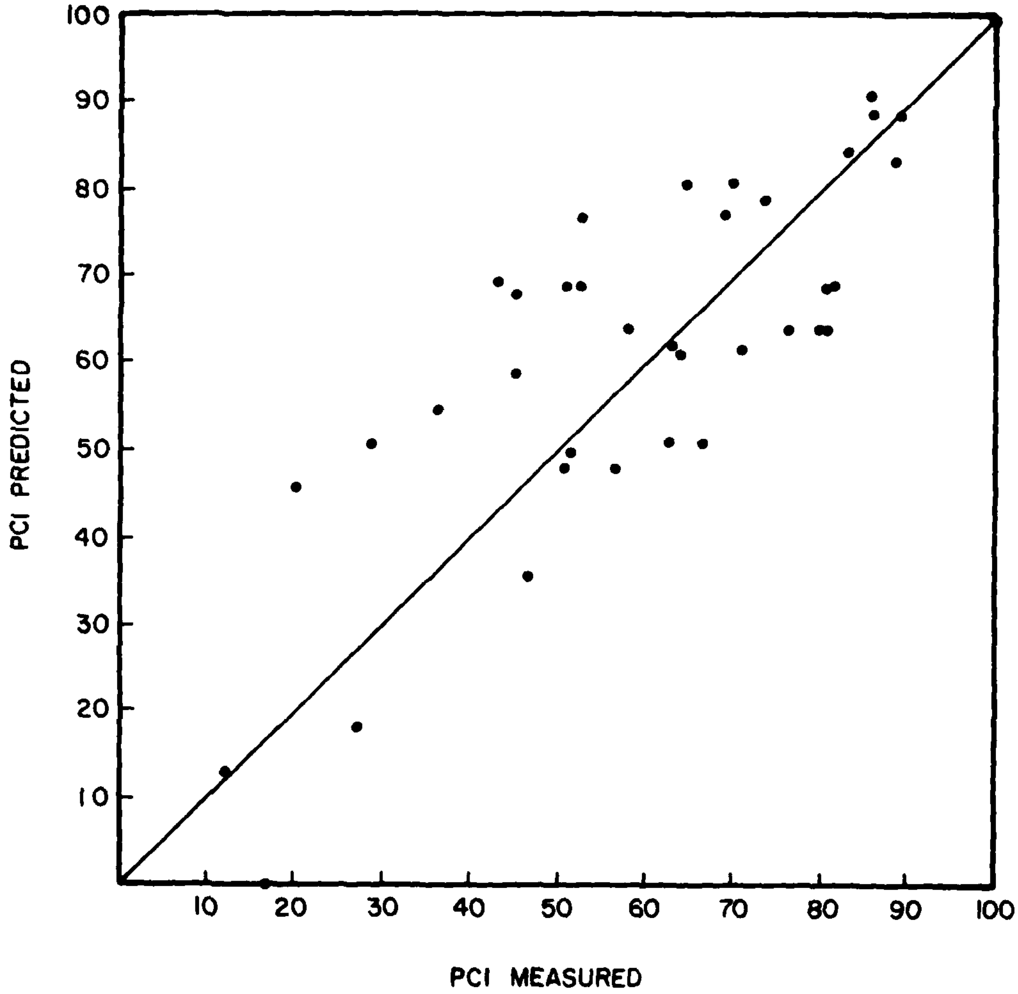

Figure 53. Comparison Between PCI Measured and PCI Predicted (Overlay + No Overlay).

The range of values for the variables included in the model are as follows:

Variable	Mean	Range
Age since original construction or last overlay (years)	15.5	0.5-35
Age overlay (years)	18.3	0 for original construction; 12-25 for overlaid pavements
Subgrade CBR (percent)	21	4-80
Base CBR (percent)	67	24-100
Pavement thickness above subgrade (inches)	22.9	10-57
AC thickness (including overlay) (inches)	4.8	2.0-12
Aircraft	--	T-37, T-38, F-4, DC-9, C-130, C-141, B-707, and B-52

Use of this model should be limited to the ranges listed above, and preferably only to the "X-Space" covering the interaction between the ranges as previously discussed for Equation 7.

PCI Sensitivity to Variables in the Prediction Model

The combined model (Equation 9) is selected for performing the sensitivity analysis because (1) its development was based on more data than used for each of the separate models, so it should be more reliable; (2) the independent variables include the effects of both the base and subgrade support, while the separate models only include the effects of one of these; and (3) the effect of number of years between original construction and overlay is included only in the combined model.

The PCI sensitivity to changes in variables was analyzed as follows:

1. Three representative levels (low, medium, and high) were selected for each variable. The following levels were selected within the ranges of the variables used in the model development:

Subgrade CBR (percent)	10,20,30
Base CBR (percent)	40,70,100
AC thickness (inches)	1,4,6
Total pavement thickness above subgrade (inches)	10,20,30

2. The PCI after 20 years from original construction (assuming no overlay) was determined by changing each variable, while keeping the remaining variables at the their average values. This was repeated for each of three types of aircraft: F-4, C-130, and C-141 (Figures 54 through 57).

3. The effect of time between original construction and overlay was demonstrated, as shown in Figure 53. The PCI after 10 years from overlay was determined for 0, 12.5, and 25 years. Zero means that the entire AC surface was constructed at the time of original construction, i.e., no overlay.

To use the model, α_{AC} and α_{SG} had to be calculated for several combinations of variables. The calculations were done as outlined in Section II, and the results are as given in Table 26. The following discusses the effect of each variable.

Subgrade CBR (Figure 54). The rate of increase of the PCI decreases as the value of the subgrade CBR increases. In addition, the effect of subgrade CBR is slightly more significant for a C-141 aircraft than for an F-4.

Base CBR (Figure 55). As the base CBR increases, the PCI increases. The increase in PCI for the C-130 aircraft is dramatic. This may be explained by the low tire pressure of the C-130 in comparison to that of the F-4 or C-141.

AC Surface Thickness (Figure 56). AC thickness significantly affects PCI for all aircrafts considered. For example, at one airfield, two 23-year-old pavement sections had PCIs of 50 and 80. The only difference between the two sections was that the AC surface thicknesses were 5 and 7.5 inches, respectively.

Pavement Thickness (Figure 57). The rate of PCI increase decreases as the pavement thickness above the subgrade increases. AC thickness is kept constant when the pavement thickness is changed. Therefore, the increase in pavement thickness is attributed to the increase in the base and subbase thickness combined.

Time Between Original Construction and Overlay (Figures 58 and 59). Figure 58 indicates that the longer the time between original construction and overlay, the lower the PCI at any specific time after the overlay, i.e., the longer the time before an overlay is placed, the faster the rate of deterioration after its placement. This can be attributed to the fact that the existing pavement condition at the time of overlay generally becomes poorer as this time is increased.

The difference in rate of deterioration between pavements that were originally constructed and those that were overlaid is further illustrated in Figure 59. This figure compares two pavements originally constructed with 5-inch and 3-inch AC, respectively. The pavement with 3-inch AC reached a minimum acceptable PCI of 40 in 15 years and thus required rehabilitation. The consequence of three alternatives is demonstrated. In this example, overlaying the pavement with 2-inch AC or reconstructing the 3-inch surface would provide the same performance. The third alternative of reconstructing the pavement with 5-inch AC would provide a much better performance. This example

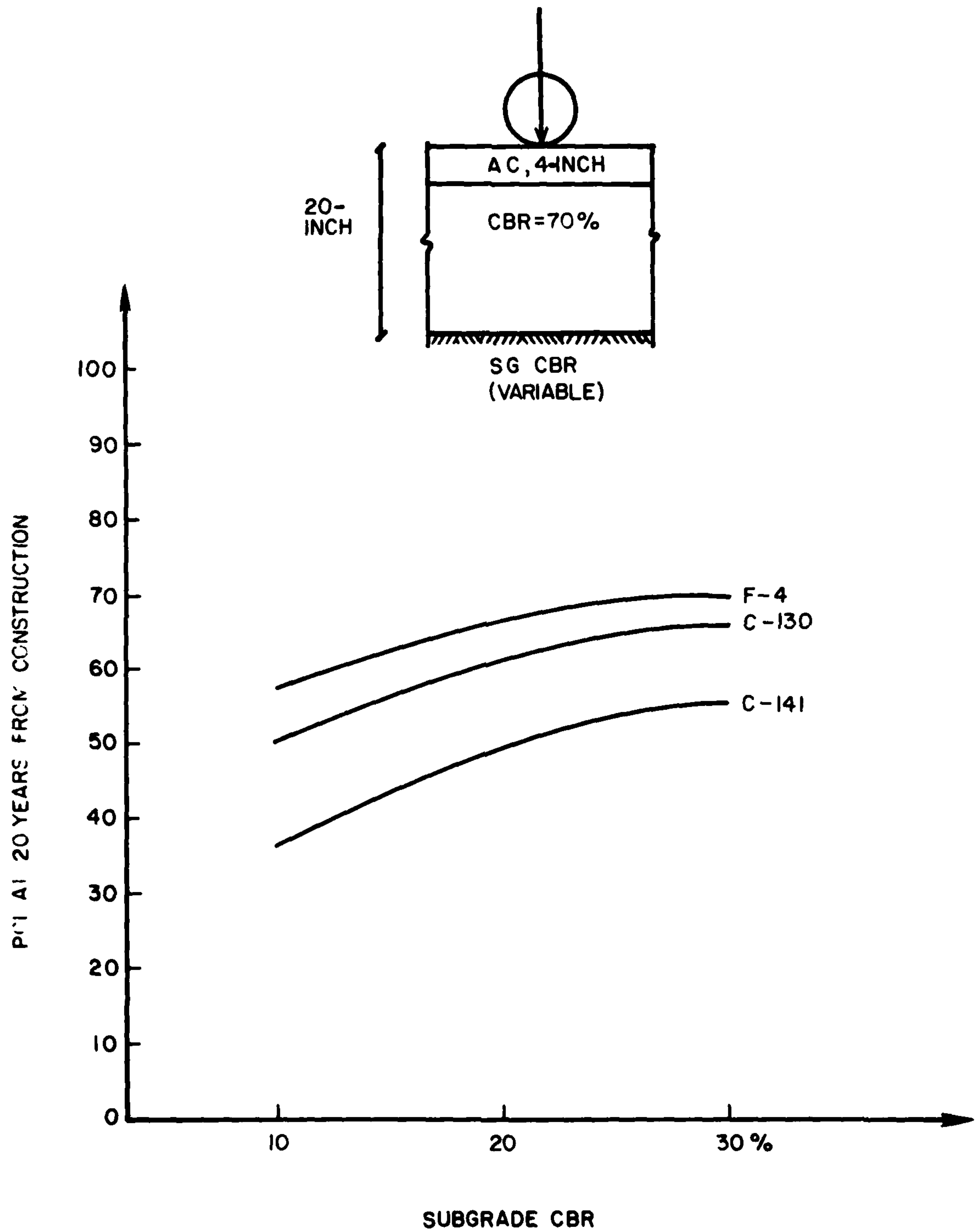

Figure 54. Example Effect of Variation in Subgrade CBR on PCI After 20 Years From Construction.

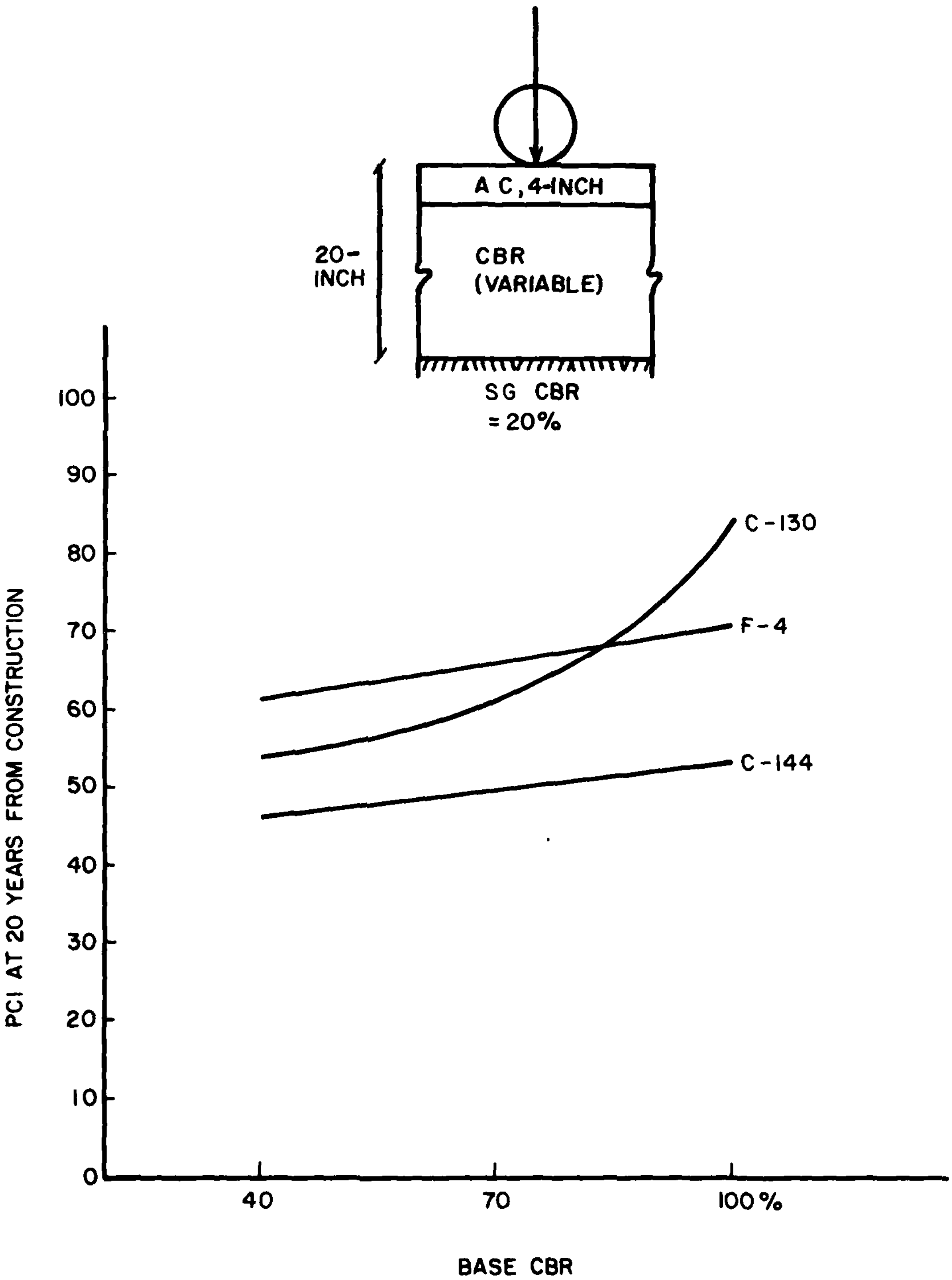

Figure 55. Example Effect of Variation in Base CBR on PCI After 20 Years From Construction.

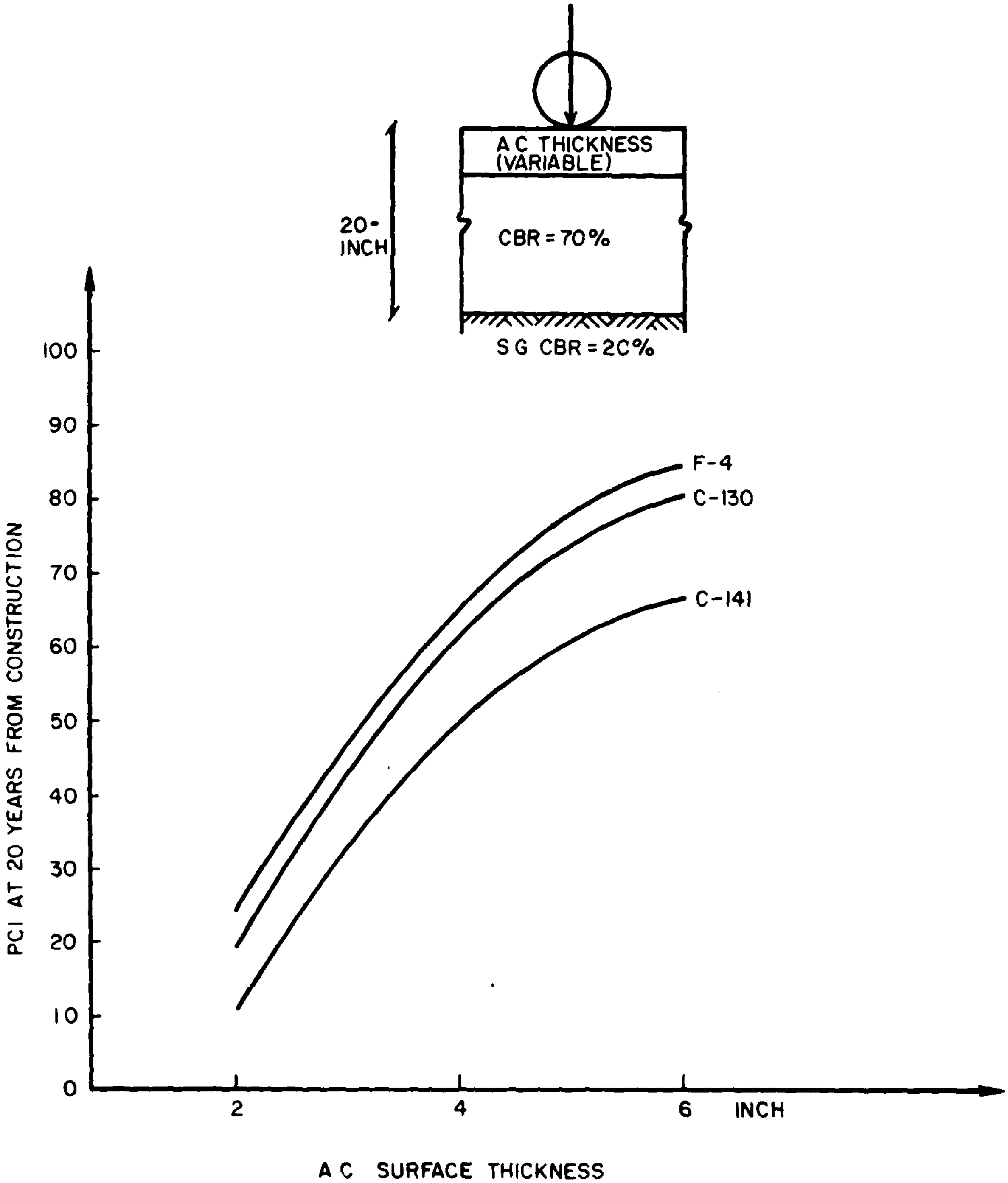

Figure 56. Example Effect of Variation in AC Surface Thickness on PCI After 20 Years From Construction.

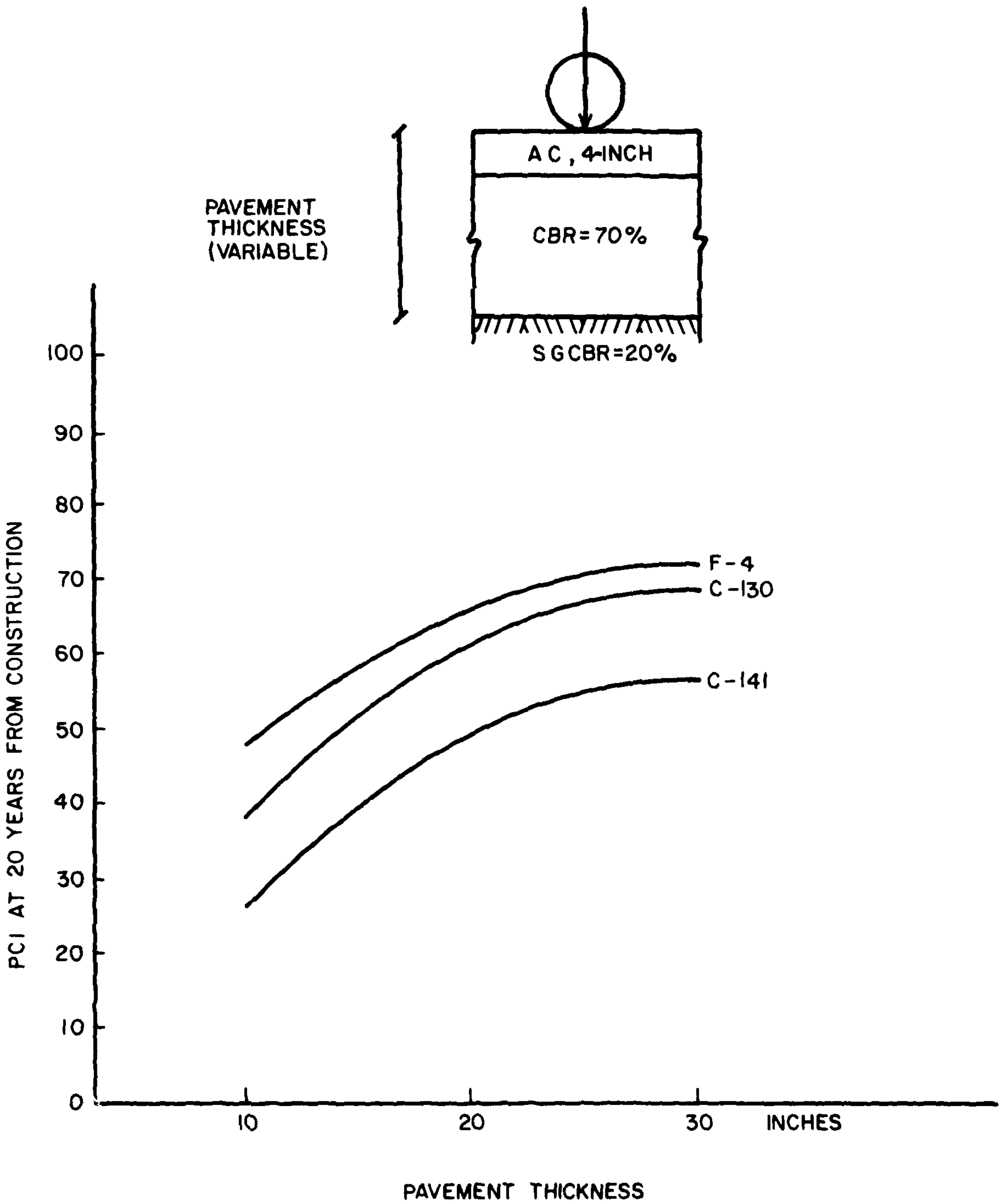

Figure 57. Example Effect of Variation in Pavement Thickness Above the Subgrade on PCI After 20 Years From Construction.

TABLE 26. CALCULATION OF α_{AC} AND α_{SG} FOR DIFFERENT PAVEMENT VARIABLES

					CALCULATION OF α_{AC}						CALCULATION OF α_{SG}					
Aircraft	Tire Contact Area (Square Inches)	No. of Controlling Wheels	Max Gross Load (kips)	Load on Controlling (kips)	AC Thickness (Inches)	ESWL, as % Load on Controlling Wheels	ESWL (kips)	$p_{e,AC}$ (psi)	Base CBR	α_{AC}	Pavement Thickness (Inches)	ESWL, as % Load on Controlling Wheels	ESWL (kips)	$p_{e,SG}$ (psi)	SG CBR	α_{SG}
									40	0.243					10	0.571
					2	100	26.3	263	70	0.339	10	100	26.3	263	20	0.832
				$\frac{60 \times 0.877}{2}$					100	0.439					30	1.037
F-4	100	1	60						40	0.486					10	1.142
				= 26.31	4	100	26.3	263	70	0.677	20	100	26.3	263	20	1.665
									100	0.878					30	2.074
									40	0.729					10	1.713
					6	100	26.3	263	70	1.016	30	100	26.3	263	20	2.497
									100	1.317					30	3.111
									40	0.203					10	0.439
					2	55.5	46.47	116	70	0.363	10	56.6	47.39	119	20	0.642
				$\frac{175 \times 0.957}{2}$					100	0.833					30	0.817
C-130	400	2	175						40	0.406					10	0.856
				= 83.73	4	55.6	46.55	116	70	0.725	20	59.9	50.15	125	20	1.249
									100	1.665					30	1.585
									40	0.605					10	1.226
					6	55.9	46.81	117	70	1.074	30	65	54.43	136	20	1.788
									100	2.417					30	2.257
									40	0.117					10	0.388
					2	32.7	50.16	241	70	0.249	10	37	56.76	273	20	0.566
				$\frac{325 \times .944}{2}$					100	0.328					30	0.704
C-141	208	4	325						40	0.348					10	0.693
				= 153.4	4	33.7	51.70	248	70	0.488	20	45.6	69.95	336	20	1.011
									100	0.64					30	1.259
									40	0.515					10	0.912
					6	34.5	52.92	254	70	0.721	30	58	88.97	428	20	1.329
									100	0.940					30	1.6[illegible]

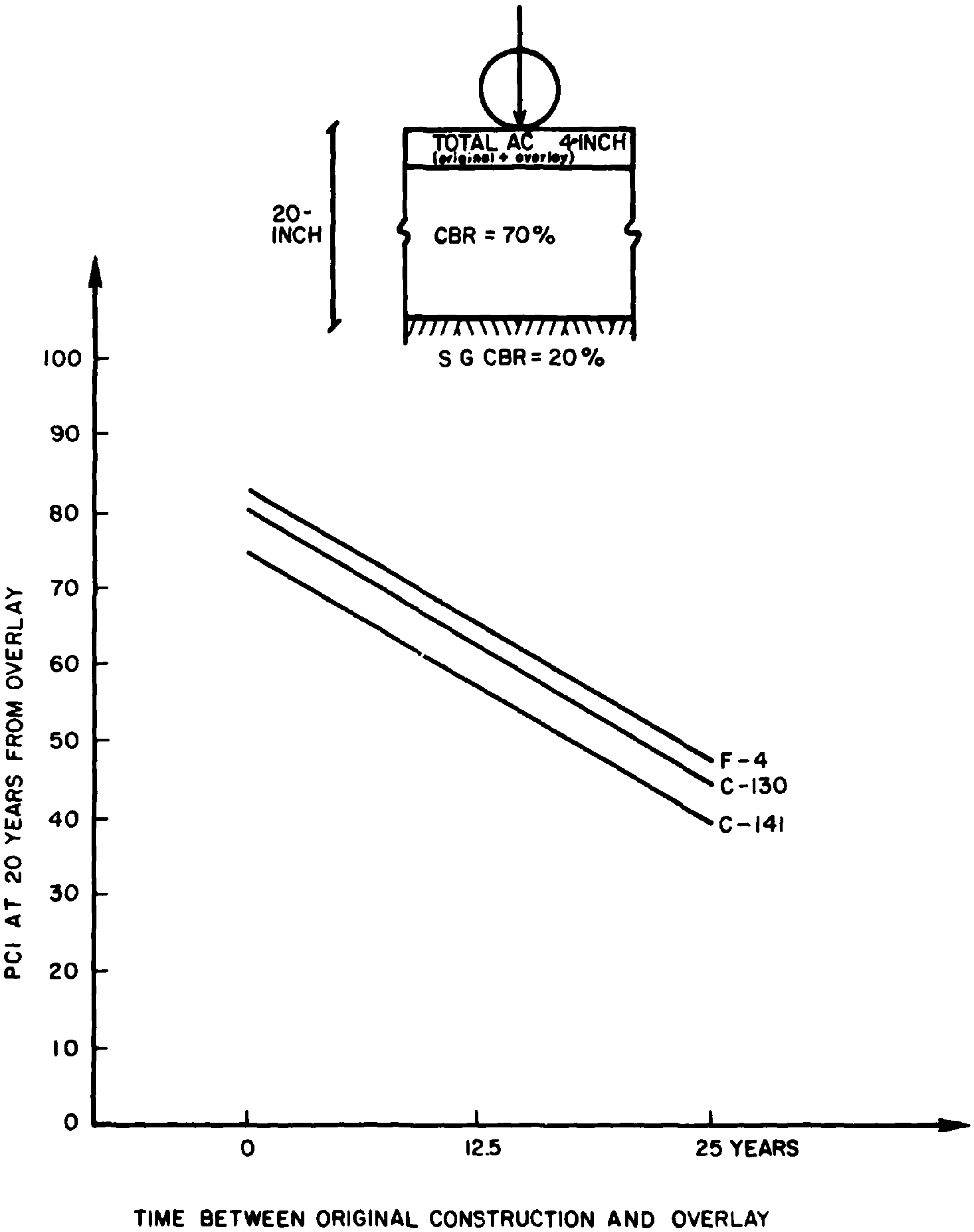

Figure 58. Example Effect of Time Between Original Construction and Overlay on PCI After 10 Years From Overlay.

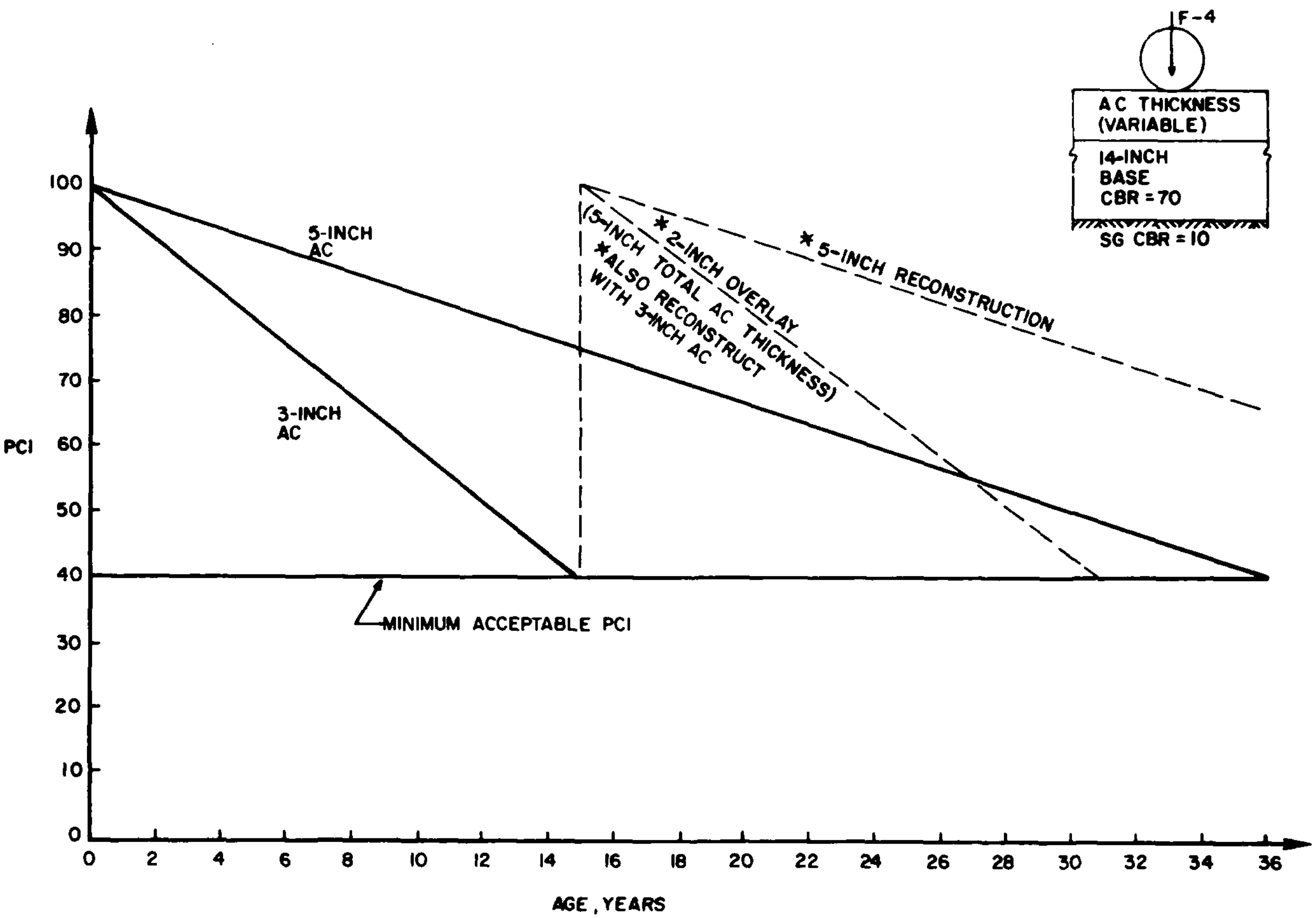

Figure 59. Example Illustration of Consequences of Pavement Overlay Versus Reconstruction.

illustrates the usefulness of the model and the information it provides for making economic analyses and rational management decisions.

MODEL FOR PREDICTION OF ALLIGATOR CRACKING IN ASPHALT PAVEMENT

Tables B-3 and B-4 of Appendix B present the data used to develop this model. The development procedure is the same as described for the PCI models.

$$\text{Percent Alligator Cracking} = \text{Age}\left[\frac{1.67}{\alpha_{SGET}} - 0.16\, t_{ACOR}\right] \qquad \text{[Equation 10]}$$

where: Age = age of pavement since original construction or last overlay (if pavement is overlaid)

α_{SGET} = load repetition factor (see Section II) computed at the subgrade level based on total equivalent thickness; the equivalency factors for different materials and layers are presented in Table 20

t_{ACOR} = thickness of the AC original surface in inches; therefore, if the pavement has been overlaid, the AC thickness of the overlay should not be included in t_{ACOR} ; the overlay thickness, however, should be included in the computation of α_{SGET}.

Following are the means and ranges of variables included in the model development.

	Mean	Range
Age since original construction or last overlay (years)	15.5	5-35
Subgrade CBR (percent)	21	4-80
Subbase thickness (inches)	9.0	0-42
Base thickness (inches)	9.0	4-27
AC thickness (including overlay)	4.8	2.0-12
AC thickness (original construction)	3.9	2.7-5

The R^2 obtained for the model is 0.68 and the standard deviation of the prediction error is 6.6. Additional independent variables such as stresses and strains obtained from mechanistic pavement models and different variable transformations and interactions should be investigated before the model is completed.

The sensitivity of percent alligator cracking to changes in variables in the model is illustrated in Figures 60 and 61 for an F-4 aircraft. The sensitivity analysis was performed by selecting three representative levels (low, medium, and high) of each variable. Using the model, the percent cracking at 10 years was computed by changing each variable and keeping the rest of the variables at their average values. This was repeated for AC thicknesses of 2, 4, and 6 inches:

Subgrade CBR (percent)	10,20,30
Base thickness (inches)	4,8,12
Base material equivalency factor*	1.0,1.25,1.5

The analysis was performed assuming a subbase thickness of 6 inches. To use the model, α_{SGET} had to be calculated for the many of combinations of variables. The calculations were performed as outlined in Section II, and the results are summarized in Table 27.

The following subsections briefly discuss the effect of changes in variables on percent alligator cracking.

Subgrade CBR (Figure 60)

As the subgrade strength increases, the percent cracking decreases with the effect leveling off at higher CBR values.

Base Thickness and Equivalency Factors (Figures 61 and 62)

Increasing the base thickness or equivalency factor* (by using stronger material) decreases cracking. The decrease levels off at a higher base thickness or equivalency factor.

AC Thickness (Figures 60 through 62)

AC thickness significantly affects percent alligator cracking. In Figure 60, the increase in AC thickness from 2 to 4 inches has a much more significant effect than the increase from 4 to 6 inches.

Pavement Overlay (Figure 63)

Figure 63 illustrates the effect of pavement overlay. The figure indicates that for a given total AC thickness, the higher the AC thickness during original construction, the less the alligator cracking will be at a given time after the overlay.

* See Section II:

Material	Equivalency Factor
Granular material	1.0
Cement-stabilized, fine-grained soil	1.25
Asphalt-stabilized sand-gravel or clay-gravel	1.5

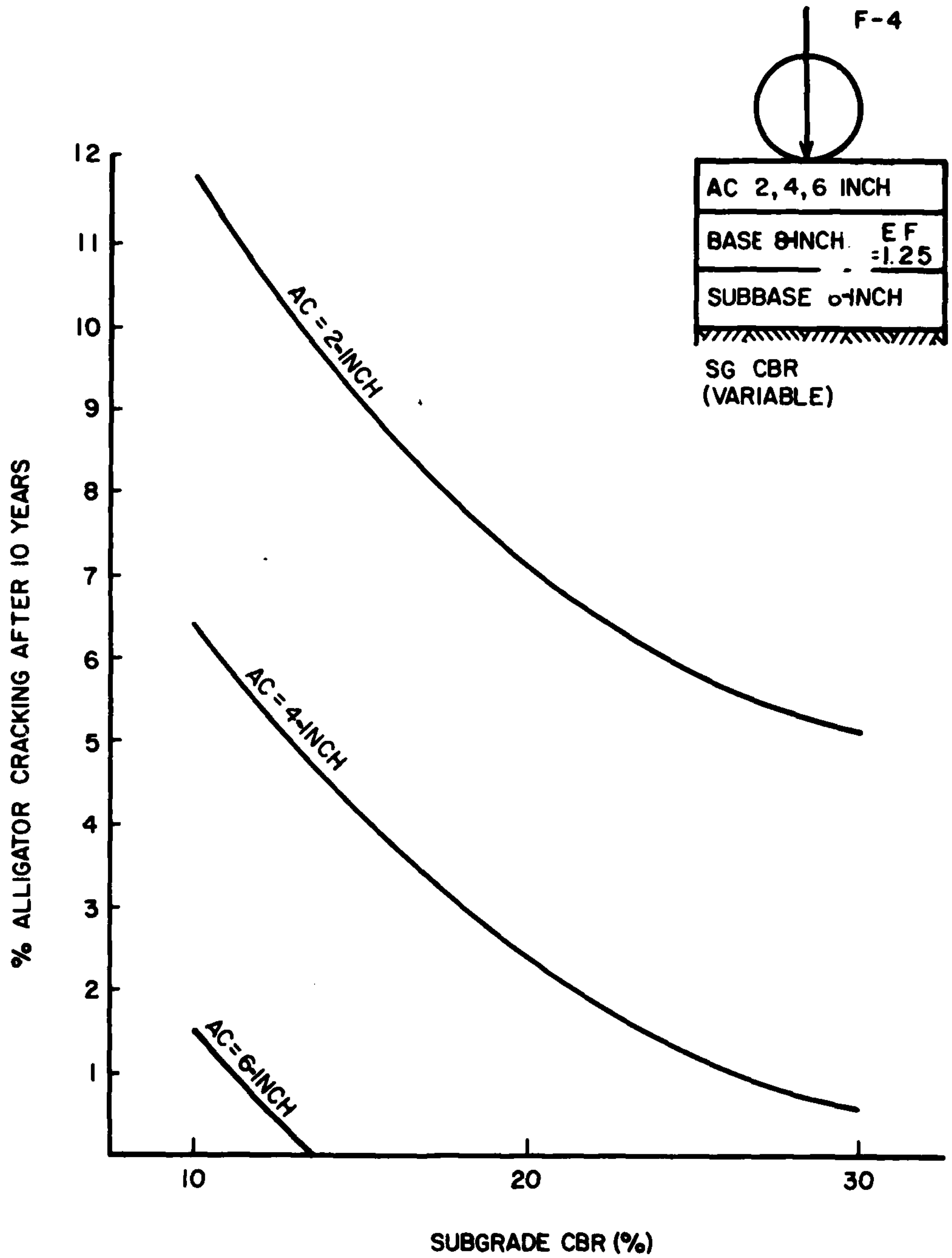

Figure 60. Example Effect of Variation in Subgrade CBR on Percent Alligator Cracking 10 Years From Original Construction.

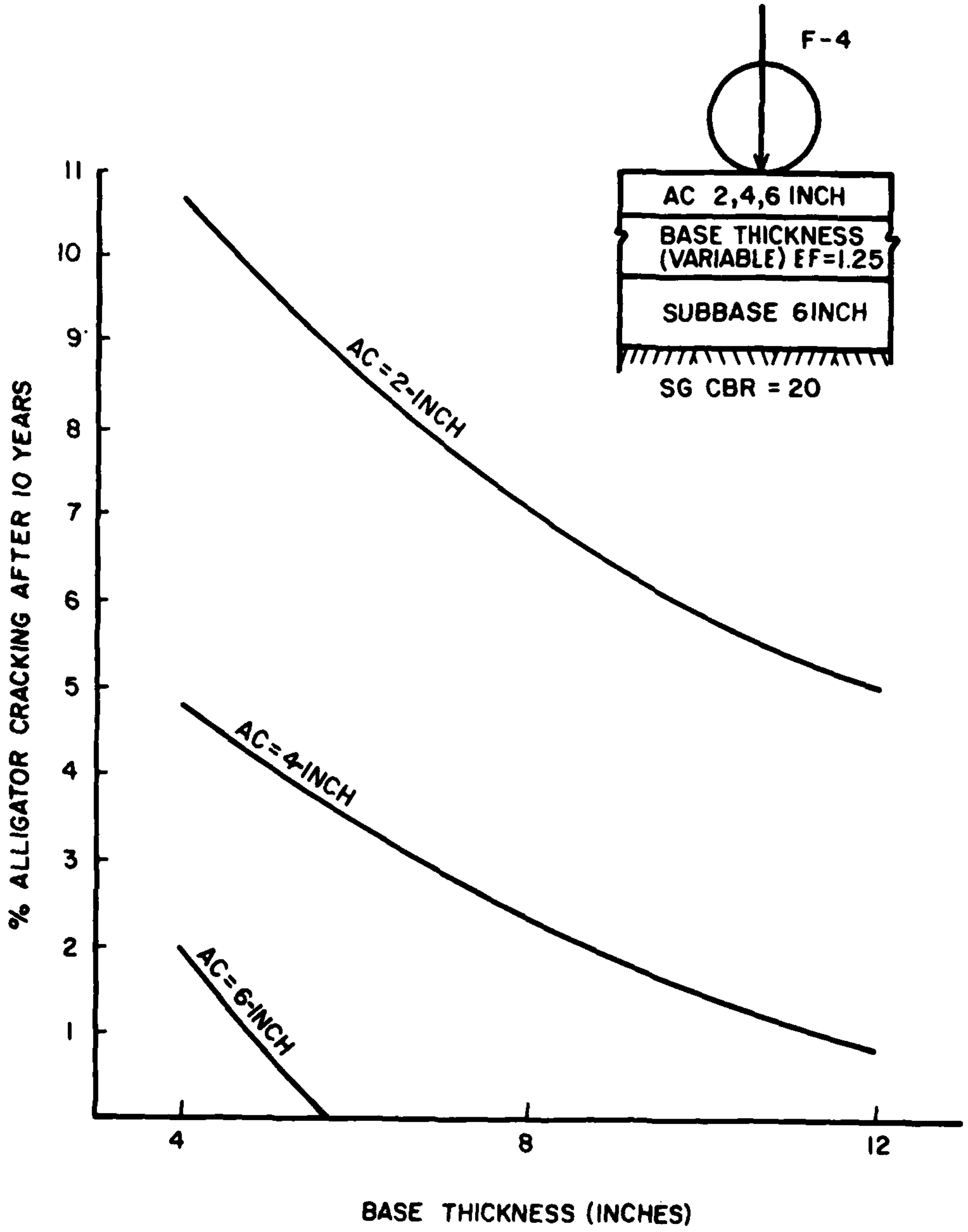

Figure 61. Example Effect of Variation in Base Thickness on Percent Alligator Cracking 10 Years From Original Construction.

TABLE 27. LOAD REPETITION FACTOR AT SUBGRADE LEVEL BASED ON TOTAL EQUIVALENT THICKNESS (α_{SGET}) FOR COMBINATION OF VARIABLES USED IN CRACKING SENSITIVITY ANALYSIS

Base Thickness (Inches)	Base Equiv Factor	AC Thickness (Inches)	Total Pavement Equiv Thickness	α_{SGET} for Subgrade CBR = 10	20	30
		2	13.4	0.765	1.115	1.389
	1.0	4	16.8	0.960	1.398	1.742
		6	20.2	1.154	1.681	2.094
		2	14.4	0.822	1.199	1.493
4	1.25	4	17.8	1.017	1.482	1.846
		6	21.2	1.211	1.765	2.198
		2	15.4	0.880	1.282	1.597
	1.5	4	18.8	1.074	1.565	1.949
		6	22.2	1.268	1.848	2.302
		2	17.4	0.994	1.448	1.804
	1.0	4	20.8	1.188	1.731	2.157
		6	24.2	1.382	2.014	2.509
		2	19.4	1.108	1.615	2.011
8	1.25	4	22.8	1.302	1.898	2.364
		6	26.2	1.496	2.181	2.717
		2	21.4	1.199	1.781	2.219
	1.5	4	24.8	1.416	2.064	2.571
		6	28.2	1.611	2.347	2.924
		2	21.4	1.199	1.781	2.219
	1.0	4	24.8	1.416	2.064	2.571
		6	28.2	1.611	2.347	2.924
		2	24.4	1.394	2.031	2.530
12	1.25	4	27.8	1.588	2.314	2.882
		6	31.2	1.782	2.597	3.235
		2	27.4	1.565	2.281	2.841
	1.5	4	30.8	1.759	2.564	3.193
		6	34.2	1.953	2.847	3.546

Note: Equivalent Factor for AC = 1.7; for F-4, Tire Contact Area = 100 Square Inches and Tire Pressure = 263 psi; Subbase = 6 Inches.

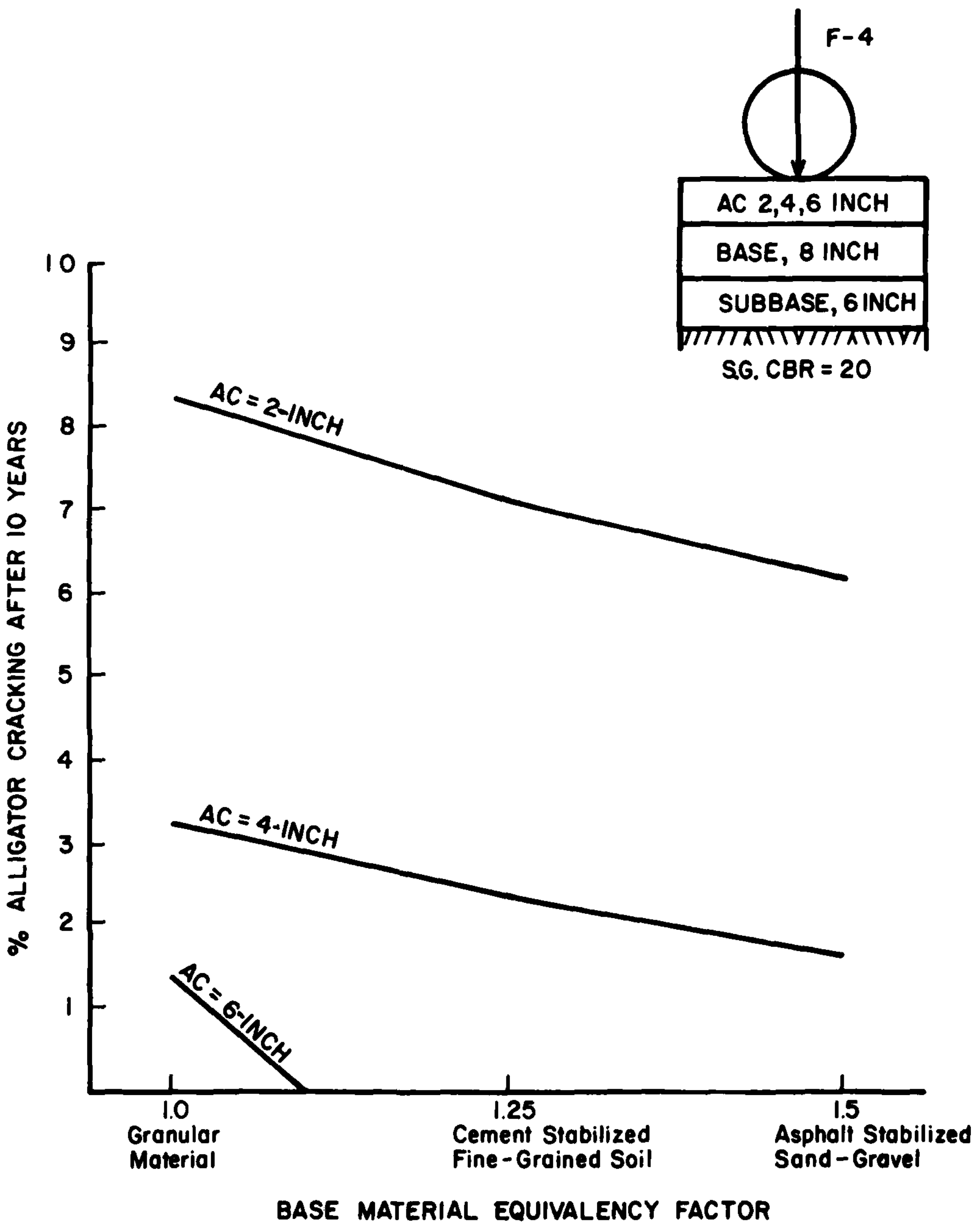

Figure 62. Example Effect of Variation in Base Materials Equivalency Factor on Percent Cracking 10 Years From Original Construction.

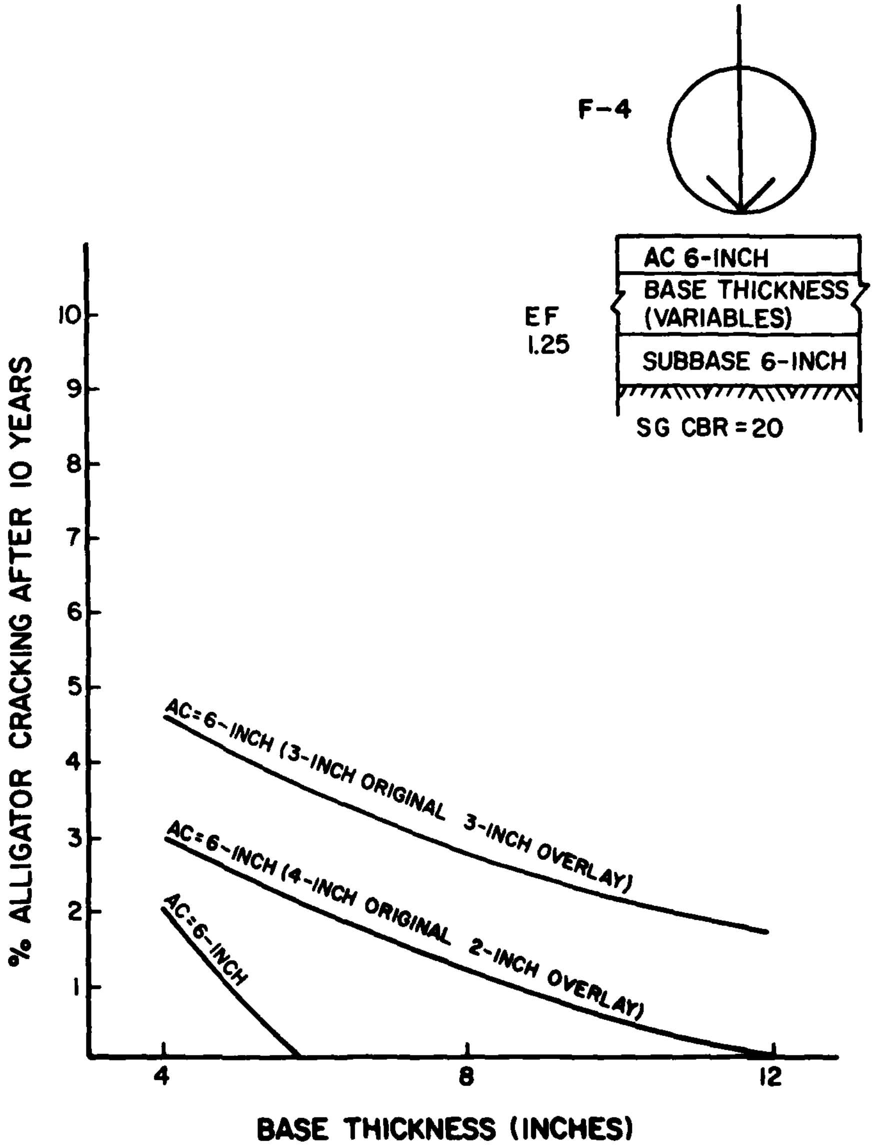

Figure 63. Example Effect of Variation in Base Thickness on Percent Alligator Cracking 10 Years From Original Construction or Overlay.

SECTION V

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS FOR PART I

SUMMARY OF MODELS

1. The model for predicting PCI for jointed concrete pavements (Equation 5) included the following variables:

   a. Age since original construction or overlay

   b. Ratio of interior slab stress to modulus of rupture

   c. Slab replacement (percent of total slabs)

   d. Slab size (longest joint spacing x shortest joint spacing)

   e. Asphalt overlay (yes or no)

   f. Average annual temperature

   g. Freezing index (degree days below 32^{o}F)

   h. Patching (percent of total slabs containing patches of more than 5 square feet <u>or</u> percentage of area patched if pavement is overlaid with AC).

Figures 30 through 33 illustrate the effect of changes in the variables on the PCI. As shown in Figure 30, slab thickness has a dramatic effect on the PCI.

2. The model for cracking in jointed concrete pavements (Equation 6) included the following variables:

   a. Age since original construction of slab

   b. Annual average temperature (^{o}F)

   c. Slab replacement (percentage of total slabs)

   d. Slab size (largest joint spacing x shortest joint spacing)

   e. Traffic area.

Figures 34 and 35 illustrate the effect of changes in the variables on slab cracking. Cracking, as defined in the model, included corner breaks, longitudinal and transverse cracking, and shattered slabs.

3. The model for predicting PCI for asphalt pavements (Equation 9) included the following variables:

a. Age since original construction or overlay

b. Age between original construction and overlay (if the pavement is overlaid)

c. Subgrade CBR

d. Base CBR

e. AC surface thickness

f. Total pavement thickness above the subgrade

g. Aircraft type (weight, gear configuration, and tire pressure).

Figures 54 through 58 illustrate PCI sensitivity to changes in the variables. Changes in the AC surface thickness significantly affect the PCI, especially at low AC thickness values. Assuming the same pavement structure, AC overlays have a much higher rate of deterioration (PCI decrease with time) in comparison to the pavements originally constructed. In addition, the longer the time span is between the original construction and the overlay, the greater the rate of deterioration will be.

4. The model for predicting percentage of alligator cracking (Equation 10) included the following variables:

a. Age since original construction or overlay

b. Subgrade CBR

c. Thickness of each layer above the subgrade

d. Material equivalency factor as determined from Table 12

e. Thickness of the originally constructed AC surface

f. Aircraft type (weight, gear configuration, and tire pressure).

Figures 60 to 63 show the effects of changes in the variables on the predicted percentage of alligator cracking.

CONCLUSIONS

Using the developed consequence models, PCI and key distress types can be predicted by means of specific pavement variables such as structural design, aircraft load, material properties, subgrade properties, and climate parameters. However, the developed models should only be considered as tentative, because additional data from many more airfield pavements are needed to develop comprehensive and reliable models useful for selecting M&R alternatives. This data collection is being planned for FY79 and FY80.

RECOMMENDATIONS

The consequence models discussed in this report should not be implemented until they are field-tested, improved, and verified. Specific recommendations for model improvements are:

1. Additional field data should be collected for the purpose of testing and improving the PCI and distress prediction models for both asphalt and jointed concrete pavements. The frequency of distribution of available data (Section II) should be used as background for designing additional data collection. For example, it is evident that for concrete pavements, more data need to be collected from pavements subjected to medium- and heavy-load aircraft (e.g., C-130, C-141, and B-52).

2. Stresses and strains obtained from pavement analysis through mechanistic models (such as the layer and finite element programs) should be investigated for use as independent variables for predicting PCI and distress over time.

3. The models presented for PCI and distress predictions are all linear with age. Nonlinear effects of age should be investigated for future models.

4. A consequence system such as that shown in Figure 65* should be developed to help the model users select cost-effective M&R strategies that are based on consequences and management policies.

* Part II of this volume.

PART II

INFORMATION REQUIREMENTS FOR PAVEMENT MANAGEMENT

SECTION VI

INFORMATION REQUIREMENTS FOR PAVEMENT MANAGEMENT

This section defines the information needed by Air Force command and base engineers to rationally manage airfield pavement M&R. This information was gathered using a three-step approach:

1. Research experience was used to develop a similar pavement information system (PAVER) for managing roads, streets, and parking lots (Reference 14). Based on this experience, it was decided that the potential users should be interviewed to determine their report and computation (information) requirements and the frequency of their use. Specific data items and data structure could then be identified for developing the pavement information system.

2. A pavement maintenance management workshop at CERL in September 1978 was attended by several command and base engineers and by representatives from the Air Force Design Center and the Directorate of Management Systems. These participants identified several report and computation requirements at both the command and base levels and discussed Air Force regulations and limitations regarding the development of a computerized information system.

3. Specific data items needed for each report were defined and recommendations were developed for data organization, software, and hardware requirements.

This section describes the recommended information and data requirements obtained as the result of this research.

REPORT AND INFORMATION REQUIREMENTS

The following subsections describe various data requirements. Each requirement heading is followed by a set of two numbers. The numbers correspond to the expected average frequency of occurrence per year per command and per base, respectively. For example, project validation is required approximately 24 times per year at the command level but only annually at the base level.

Project Validation (24/1)

Major command engineers are required to validate M&R projects submitted by base engineers in terms of need, scope, and method of repair. A rational procedure for performing a validation was developed, using the input of several command engineers (Reference 15). Figure 64 is the evaluation summary sheet on which the validation was based. All the information shown in the figure should be available to command and base engineers who will perform the validation.

Facility:______________ Feature:_____________

1. Overall Condition Rating - PCI
   Excellent, Very Good, Good, Fair, Poor, Very Poor, Failed.

2. Variation of Condition Within Feature - PCI

   a. Localized Random Variation — Yes, No
   b. Systematic Variation — Yes, No

3. Rate of Deterioration of Condition - PCI

   a. Long-term period (since construction) — Low, Normal, High
   b. Short-term period (1 year) — Low, Normal, High

4. Distress Evaluation

   a. Cause

      Load Associated Distress ____ percent deduct values
      Climate/Durability Associated ____ percent deduct values
      Other (_____) Associated Distress ____ percent deduct values

   b. Moisture (Drainage) Effect on Distress — Minor, Moderate, Major

5. Load Carrying Capacity Deficiency — No, Yes

6. Surface Roughness — Minor, Moderate, Major

7. Skid Resistance/Hydroplaning (runways only)
   - No hydroplaning problems are expected
   - Transitional
   - Potential for hydroplaning
   - Very high probability

   b. Stopping Distance Ratio
   - No hydroplaning anticipated
   - Potential not well defined
   - Potential for hydroplaning
   - Very high hydroplaning potential

   c. Transverse Slope — Poor, Fair, Good, Excellent

8. Previous Maintenance — Low, Normal, High

9. Effect on Mission (Comments):____________________________

____

____

Figure 64. Airfield Pavement Condition Evaluation Summary.

Determination of Consequence of Various M&R Alternatives and Changes in Mission (9/5)

A system was needed that could be used to determine the consequence of (1) selecting specific M&R strategies, and (2) changes in mission. "Consequence" is defined as PCI, major distress types, M&R needs and costs, and repair time over a future time period. Figure 65 shows the overall flow chart for the consequence system, including needed inputs. As shown, the inputs to the overall consequence system include results of computations from other subsystems: economic analysis, PCI determination, PCI and distress prediction, and load-carrying capacity. Each subsystem is also a stand-alone model that provides answers to other requirements, which are briefly described below.

Economic Analysis (2/4). A present-worth economic analysis to compare various M&R strategies is based on initial cost, annual M&R cost, and salvage value (Reference 15).

PCI Determination (0/3). A computer program for calculating PCI has been developed and implemented by the Air Force worldwide (Reference 5). The program, which is based on distress data gathered from pavement condition surveys, is a tool for expedient determination of the PCI. The PCI for individual pavement features is needed to determine pavement condition rating and as input for many other report and computation requirements.

PCI and Distress Prediction (3/3). Models are currently being developed (Sections II, III, and IV) for predicting PCI and major distress types over time as a function of traffic, climate, pavement structure, material properties, and applied M&R. The output from these prediction models will provide much needed information for project programming documents.

Load-Carrying Capacity (12/3). A computer program, based on pavement structure and materials properties (Reference 13) already exists for determining allowable aircraft loads. This information is useful for recommending use of the airfield by aircraft different from those used in current airfield mission, project validation, design of repair alternative, etc.

Project Estimating (30/3)

The estimated cost of various M&R projects, based on unit costs in local areas, must be developed. This information is especially useful for preparing and reviewing project programming documents.

Annual and 5-Year Work Plans (2/2)

Current (annual) and future (5-year) project requirements must be developed, reviewed, and updated.

Evaluation Reports (1/1)

Pavement evaluation reports for individual bases must be developed and updated.

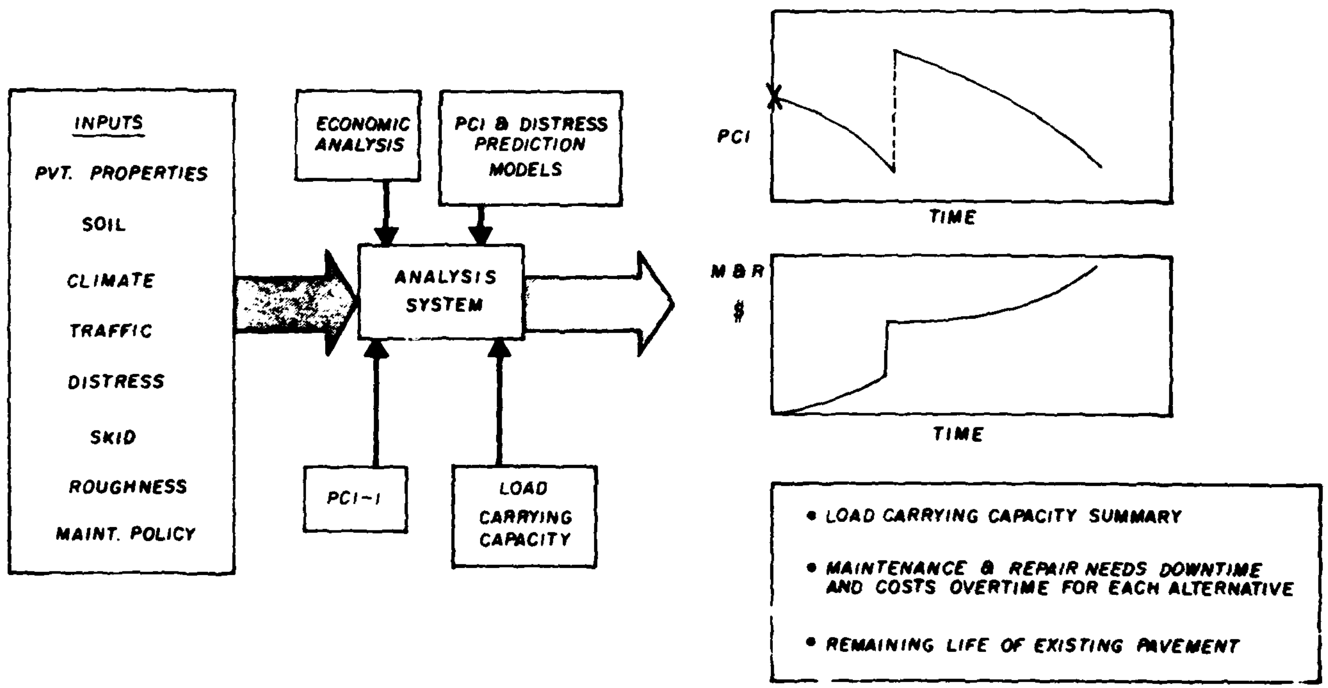

Figure 65. M&R Consequence System.

Visitation of Bases by Command Engineers (12/0)

Command engineers usually visit their bases to review pavement condition and project requirements. They indicated that it would be beneficial to have the following information prior to the visits:

a. Past condition records

b. Changes in conditions

c. Information to assist them in briefing base/wing commanders.

Project Priorities (2/1)

Command engineers require information to determine command project priorities among all bases, while base engineers are usually concerned with project priorities at their own bases.

Optimization of Limited Budget Spending (4/0)

Command engineers have expressed the need for optimizing limited funds, since the available pavement M&R budget is usually less than the required amount.

The report needs for the eight requirements presented above are classified in Table 28 in terms of their status during FY78. The reports are classified into three categories: PRODUCTION (already implemented by the Air Force); PILOT (proposed for pilot testing during FY79 and 80); and LONG RANGE (proposed for testing and implementation after FY80).

DATA REQUIREMENTS

Table 29 provides a tentative list of data elements needed to generate the information requirements. The data elements are classified into data groups, i.e., Facility Identification, Feature Identification, Condition History, etc. The last column of the table shows the expected frequency of use for each data element per year for the command and the base, respectively. The frequency is based on the expected generation frequency of each report. Since each data element may be used to generate more than one report, data structure is very important in minimizing the cost of report generation.

TABLE 28. BREAKDOWN OF STATUS OF AVAILABILITY OF DIFFERENT REPORTS AS PRODUCTION, PILOT, AND LONG RANGE

Report Requirement	Production (Before 1979)	Pilot (1979-1980)	Long Range (After 1980)
1. Project Validation		★	
2. Consequence System			★
Economic Analysis		★	
PCI Determination	★		
PCI and Distress Prediction		★	
Load Carrying Capacity	★		
3. Project Estimating			★
4. Annual and 5-Year Work Plans			★
5. Evaluation Reports			★
6. Visitation of Bases by Command Engineers		★	
7. Project Priorities			★
8. Optimization of Limited Budget Spending			★

TABLE 29. DATA ELEMENTS NEEDED TO GENERATE INFORMATION REQUIREMENTS

ITEM	Elements	Report 1 (24/1)	2 (9/5)	2.1 (2/4)	2.2 (0/3)	2.3 (3/3)	2.4 (12/3)	3 (30/3)	4 (2/2)	5 (1/1)	6 (12/0)	7 (2/2)	8 (4/0)	
Facility	Facility update	✓	✓				✓			✓				(46/10)
	Facility Name	✓	✓				✓			✓	✓	✓		(60/12)
	Facility use	✓	✓			✓	✓	✓	✓	✓		✓	✓	(87/20)
	Number of feature	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓		(94/24)
	Facility Area								✓			✓	✓	(8/4)
	Base Name	✓	✓						✓	✓	✓	✓	✓	(54/11)
Feature ID	Feature Update	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	(101/27)
	Feature Number	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	(101/27)
	From													
	To													
	Feature area	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	(101/27)
	Feature Length	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	(101/27)
	Feature Width	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	(57/14)
	Pavement rank	✓	✓			✓			✓	✓	✓	✓	✓	(101/27)
	Surface type	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	(101/27)
	Slab width		✓			✓		✓	✓	✓	✓			(57/14)
	SLAB LENGTH		✓			✓		✓	✓	✓	✓			(57/14
	Total Slabs/feature	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	(89/24)

TABLE 29. DATA ELEMENTS NEEDED TO GENERATE INFORMATION REQUIREMENTS (CONTINUED)

ITEM	Elements	Report 1 (24/1)	2 (9/5)	2.1 (2/4)	2.2 (0/3)	2.3 (3/3)	2.4 (12/3)	3 (30/3)	4 (2/2)	5 (1/1)	6 (12/0)	7 (2/2)	8 (4/0)	
Condition History	Inspection Day	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	(89/24)
	Roughness	✓	✓						✓	✓	✓	✓	✓	(54/11)
	Skid number	✓	✓						✓	✓	✓	✓	✓	(54/11)
	Skid SDR	✓	✓						✓	✓	✓	✓	✓	(54/11)
	Transverse Slope	✓	✓						✓	✓	✓	✓	✓	(54/11)
	Previous maintenance	✓	✓						✓	✓	✓	✓	✓	(54/11)
	Long term deterioration	✓	✓						✓	✓	✓	✓	✓	(54/11)
	Short term deterioration	✓	✓						✓	✓	✓	✓	✓	(54/11)
	Localized variation	✓	✓						✓	✓	✓	✓	✓	(54/11)
	Systematic variation	✓	✓						✓	✓	✓	✓	✓	(54/11)
	Load deficiency	✓	✓						✓	✓	✓	✓	✓	(54/11)
	Drainage Condition	✓	✓						✓	✓	✓	✓	✓	(54/11)
	Shoulder Condition													
	Total number of samples	✓	✓		✓	✓				✓	✓			(49/13)
	Number of samples surveyed	✓	✓		✓	✓				✓	✓			(49/13)
	PERCENT DEDUCT LOAD	✓	✓						✓	✓	✓	✓	✓	(54/11)

TABLE 29. DATA ELEMENTS NEEDED TO GENERATE INFORMATION REQUIREMENTS (CONTINUED)

ITEM	Elements	Report 1 (24/1)	2 (9/5)	2.1 (2/4)	2.2 (0/3)	2.3 (3/3)	2.4 (12/3)	3 (30/3)	4 (2/2)	5 (1/1)	6 (12/0)	7 (2/2)	8 (4/0)	
	Moisture Distress	✓	✓						✓	✓	✓	✓	✓	(54/11)
	Other Deduct	✓	✓						✓	✓	✓	✓	✓	(54/11)
	Condition History Comments													
	Total Random Size				✓	✓				✓				(4/7)
	Total Additional Size				✓	✓				✓				(4/7)
	PCI	✓	✓			✓				✓	✓	✓	✓	(55/12)
	PCI Samp (Min)	✓							✓	✓	✓	✓	✓	(45/6)
	PCI Samp (Max)	✓							✓	✓	✓	✓	✓	(45/6)
	PCI Std Dev	✓							✓	✓	✓	✓	✓	(45/6)
Sample Unit	Sample Unit Number				✓					✓				(1/4)
	Sample Type				✓					✓				(1/4)
	Sample Size				✓					✓	✓			(13/4)
	Sample PCI	✓			✓					✓	✓			(37/5)
Pavement Distress	Distress Code	✓	✓		✓	✓		✓	✓	✓	✓	✓	✓	(87/20)
	Distress Type	✓	✓		✓	✓		✓	✓	✓	✓	✓	✓	(87/20)
	Quantity	✓	✓		✓	✓		✓	✓	✓	✓	✓	✓	(87/20)

TABLE 29. DATA ELEMENTS NEEDED TO GENERATE INFORMATION REQUIREMENTS (CONTINUED)

ITEMS	ELEMENTS	Report 1 (24/1)	2 (9/5)	2.1 (2/4)	2.2 (0/3)	2.3 (3/3)	2.4 (12/3)	3 (30/3)	4 (2/2)	5 (1/1)	6 (12/0)	7 (2/2)	8 (4/0)	
	Severity	✓	✓		✓	✓		✓	✓	✓	✓	✓	✓	(87/20)
	Distress Unit	✓	✓		✓	✓		✓	✓	✓	✓	✓	✓	(87/20)
Work Record	Percent Slab Replacement													
	Percent Deep or Partial Depth Patch													
	Work Code	✓	✓			✓			✓	✓	✓	✓	✓	(57/14)
	Work Description	✓	✓			✓			✓	✓	✓	✓	✓	(57/14)
	Distress	✓	✓			✓			✓	✓				(39/15)
	Material Code	✓	✓			✓			✓	✓				(39/15)
	Material Description	✓	✓			✓			✓	✓				(39/15)
	Manner of Accomplishment	✓	✓			✓			✓	✓	✓	✓	✓	(57/14)
	Date Reported	✓	✓			✓			✓	✓	✓	✓	✓	(57/14)
	Date Completed	✓	✓			✓				✓	✓	✓	✓	(57/14)
	Thickness	✓	✓			✓			✓	✓				(68/14)
	Work Quantity	✓	✓			✓			✓	✓	✓	✓	✓	(57/14)
	Work Units	✓	✓			✓			✓	✓	✓	✓	✓	(57/14)
	Total Cost	✓	✓			✓			✓	✓	✓	✓	✓	(57/14)
	Work Comments								✓	✓	✓			(15/6)

TABLE 29. DATA ELEMENTS NEEDED TO GENERATE INFORMATION REQUIREMENTS (CONTINUED)

ITEM	ELEMENTS	Report 1 (24/1)	2 (9/5)	2.1 (2/4)	2.2 (0/3)	2.3 (3/3)	2.4 (12/3)	3 (30/3)	4 (2/2)	5 (1/1)	6 (12/0)	7 (2/2)	8 (4/0)	
Pavement Structure and Sub-grade	Date Constructed	✓	✓			✓	✓			✓				(49/13)
	Layer Category	✓	✓			✓	✓			✓				(49/13)
	Layer Material Code	✓	✓			✓	✓			✓				(49/13)
	Layer Material	✓	✓			✓	✓			✓				(49/13)
	Layer Thickness	✓	✓			✓	✓			✓				(49/13)
	Layer Comments									✓				(1/1)
	Pavement Structure Update									✓				(1/1)
Layer Material Properties	Test Date	✓	✓			✓	✓	✓	✓	✓				(81/18)
	Test Type and Method	✓	✓			✓	✓	✓	✓	✓				(81/18)
	Test Value	✓	✓			✓	✓	✓	✓	✓				(81/18)
Traffic Record	Traffic Survey Date	✓	✓			✓	✓		✓	✓				(81/18)
	Aircraft	✓	✓			✓	✓		✓	✓	✓	✓	✓	(69/17)
	Passes Per Month	✓	✓			✓	✓		✓	✓	✓	✓	✓	(69/17)
	Traffic Record Comments	✓	✓						✓	✓				(36/9)
Main-tenance	Maintenance Policy Update													
	Dist. Code Before Repair, After Repair		✓	✓	✓			✓	✓		✓			(55/17)
	Dist. Core Before Repair, After Repair		✓	✓	✓			✓	✓		✓			(55/17)

TABLE 29. DATA ELEMENTS NEEDED TO GENERATE INFORMATION REQUIREMENTS (CONTINUED)

ITEM	ELEMENTS	Report 1 (24/1)	2 (9/5	2.1 (2/4)	2.2 (0/3)	2.3 (3/3)	2.4 (12/3)	3 (30/3)	4 (2/2)	5 (1/1)	6 (12/0)	7 (2/2)	8 (4/0)	
	Severity of Dist Before Repair, After Repair		✓	✓	✓			✓	✓		✓			(55/17)
	Repair Code		✓	✓	✓			✓	✓		✓			(55/17)
	Repair Type		✓	✓	✓			✓	✓		✓			(55/17)
	Repair Material Code		✓		✓			✓	✓		✓			(53/13)
	Repair Material		✓		✓			✓	✓		✓			(53/13)
	Labor Hours Per Unit							✓			✓			(42/3)
	Labor Cost Per Unit							✓			✓			(42/3)
	Equipment Cost Per Unit							✓			✓			(42/3)
	Material Cost Per Unit							✓			✓			(42/3)
	Total Cost Per Unit		✓	✓					✓		✓			(25/11)
	Repair Unit		✓	✓	✓			✓	✓		✓			(53/17)
Climate	Month		✓			✓				✓				(13/9)
	Extreme Max. Temp		✓			✓				✓				(13/9)
	Mean Max. Temp		✓			✓				✓				(13/9)
	Mean Min Temp		✓			✓				✓				(13/9)

TABLE 29. DATA ELEMENTS NEEDED TO GENERATE INFORMATION REQUIREMENTS (CONCLUDED)

ITEM	ELEMENTS	1	2	2.1	2.2	2.3	2.4	3	4	5	6	7	8	
	Extra Min Temp		✓			✓				✓				(13/9)
	Mean Preciptation		✓			✓				✓				(13/9)
	Mean Solar Radiation		✓			✓				✓				(13/9)
	Mean Wind Speed		✓			✓				✓				(13/9)

SECTION VII

IMPLEMENTATION ALTERNATIVES FOR COMPUTER-AIDED PAVEMENT MANAGEMENT ASSUMPTIONS

The contents of this section are based on data gathered during a 1-day meeting with Air Force engineers and personnel at Tyndall Air Force Base, a 2-day workshop at CERL, and numerous discussions among the project staff. Because operating cost data for existing Air Force standard computer systems and software development cost data for the Air Force System Development Center are not available at this time, the cost analysis only includes commercial systems. Several assumptions were made during this study:

1. It is desirable and essential to develop a pavement maintenance information system. Although the use of such a system may not reduce personnel requirements, it will greatly assist the civil engineer in the decision-making process and hence increase cost avoidance and productivity.

2. It is very desirable to use standard Air Force computer systems when possible. Any system development effort that exceeds $50,000 in hardware purchase or 10 man-years in software development requires submittal of detailed justifications and perhaps a long delay before project approval.

3. The Air Force System Design Center is responsible for all development and maintenance of standard Air Force computer systems. Thus, this section will emphasize the specifications and requirements of the Pavement Maintenance Information System (PMIS), rather than implementation-related issues.

REPORT AND DATA REQUIREMENTS

The data requirements for determining M&R consequence and pavement management are related to the development of PMIS in the following ways:

1. The civil engineers at the Air Force Headquarters, major commands, and bases are potential users of the proposed PMIS. However, most of the data on Air Force airfield pavements are located at the bases.

2. Manual methods are currently used for report preparation and pavement condition analysis to determine M&R needs.

3. The frequency of information requests and the volume of items per report are low (hundreds of reports are required per year, and there are numerous items in most reports). Thus, although the batch process may not be desirable for long-term operations, it is sufficient at present. However, using an interactive system would greatly enhance the effectiveness of the economic analysis and/or pavement condition forecasting models.

4. As with other new computer applications, the types of reports and the items in the reports are not yet well defined.

5. The major benefit of such a system is based on the development of economic analysis and performance prediction models (consequence system) for Air Force airfield pavement. These functions are only possible when enough long-term structural, condition, and performance data are collected and stored.

6. Because report requirements and format are not specifically defined, and because the development of the consequence system has not been completed, the data items were identified by CERL after consulting with civil engineers from the Air Force Civil Engineering Center, major commands, and bases. The data items included in this report will require further scrutiny while PMIS is being implemented.

7. Each of the three levels of system users requires access to certain data. Base engineers must have access to data generated from their bases, major command engineers must have access to data generated from all bases under their command, and the Air Force Headquarters engineers must have access to data from all bases.

SYSTEM REQUIREMENTS

PMIS operational requirements include the mode of operations, turnaround time for report generation, storage size, file and data base management facilities, and system organization. The subsequent discussions of each requirement are based on purely technical factors, not on the Air Force computer system environment.

Operation Mode and Turnaround Time

The interactive mode (i.e., direct user input and computer response via terminal) is best suited for the economic analysis and pavement condition forecasting models (consequence system). In computer-based modeling and simulation, a user often inputs a set of values, waits for the results, and then modifies the input to obtain a better set of results. This process is repeated until a satisfactory set of results is obtained. The batch process* is undesirable under these circumstances because it is very time-consuming.

With the exception of the economic analysis and/or pavement condition forecasting models, the turnaround time for most of the reports is a matter of hours (or overnight). The batch process is therefore acceptable.

Storage Requirements

The data requirements of the PMIS have not been completed, so extra storage space must be reserved in anticipation of future expansions. However, with proper data compression and encoding, storage requirements for each base should not exceed a few thousand bytes per year. A well-developed data base management facility (such as System 2000) should be used during the pilot

*Batch process: programs and data in one batch and await turn for execution by computer. No direct user-computer interaction.

testing period and is preferable when the system is fully implemented. Such a system usually increases the flexibility for changing data format and hence reduces software development costs.

Data Bases and Data Base Organizations

Because there are three levels of Air Force organizational structure (Headquarters, major commands, and bases), access right must be regulated and the physical location of data bases must be selected. A central data bank and a single computer for all Air Force pavement maintenance data storage and processing would be one way to organize the data base. The opposite type of organization would be a distributed data base system, where each base has its portion of the data on its own machine and permits the major command and Air Force Headquarters to have online access to these data. A compromise would be placing a centralized data base for all bases within each major command. With this method, the Air Force Headquarters could access the distributed data for their report generation, while the base engineers could "dial in" to their respective major command machines to access their data. The technical and operational advantages and disadvantages of each model are discussed in the following subsections.

The Centralized Data Base. The major advantage of a centralized data base is the simplicity of data access for all users. A modern Data Base Management System (DBMS) usually has security features for multiple access rights to facilitate access by Headquarters, commands, and bases. An advantage associated with the simple data bank structure is the low software development and system operation costs. In addition, a centralized facility usually provides better staff support and greater data uniformity throughout all bases and commands.

A major disadvantage of a centralized data base is the necessity for telecommunication between terminals located at the bases and commands and the central data bank (assuming that interactive computing is a requirement). Another disadvantage is the lack of a large enough computer, sufficient storage space, and a good DBMS. It is not known whether the current Air Force Headquarters computer will provide this level of support. However, use of a minicomputer for PMIS will eliminate this problem.

A Totally Distributed Data Base. A totally distributed data base organization permits each base to maintain its own data and to use its existing standard Air Force computer. However, the disadvantages of such an organization are numerous. The cost associated with system development is much greater than that of the centralized data base method, because of the additional complexity in the multiple levels of data base management. Most of this cost increase will occur at the command and Headquarters levels. In addition, the cost associated with the system operations of a distributed data base is greater, because (1) there must be a procedure to enforce data uniformity throughout all bases, and (2) computer supports are necessary at all levels (these supports include a data management system, competent system analysts and operators, and availability of machine time and space).

Therefore, the totally distributed data base organization is not recommended for the PMIS data base; however, it may be used for stand-alone computational programs such as the PCI program, which is currently operational at the base level.

Command-Level Data Base. A centralized data base at each major command provides the command engineers with access to a single data base, using a machine that is available locally. A command's base engineers will access the data base via remote terminals. The advantages of such an arrangement are: (1) the development of PMIS for major commands based on a centralized command-level data base is much simpler than that of the total distributed data base method; (2) it will be more convenient to pilot test the PMIS which covers many different bases within one command; and (3) the standard Air Force command computer is larger, and therefore better equipped with data base management facilities than a base computer.

The disadvantages of such an arrangement are: (1) the need to provide remote access for base engineers under each major command; and (2) the possible need to merge data bases from every command of Air Force Headquarters.

For economic reasons, certain data should be stored at the base level rather than at the command level. More specifically, data related to sample units which are used only for computing PCI should be stored in the base machine. Thus, PCI will be computed by the base computer (as is currently done) before it is submitted to the centralized command data base.

Recommendation for Data Base Organization. The centralized data base at the command level is clearly the best data base organization, because of the facts discussed above and because it may also use existing Air Force standard computer systems. Furthermore, the PMIS needs are better defined for command and base engineers than for Air Force Headquarters engineers. Therefore, it is logical to design a PMIS addressing the needs of the command and base levels now and to extend the supports to Headquarters later.

Data Base Management

This discussion of data base management requires the reader to understand the meanings of the three terms briefly defined below:

Data base: a collection of records

Record: a collection of data items; for example, data related to condition of a pavement feature

Data item: the smallest element by which data can be retrieved; for example, PCI.

Data base management includes organizing the data (data structure) and accessing the data in the data base.

Data Organization. There are several data structures, including sequential, index sequential, tree, and graph. In the sequential organization (Figure 66), data items are stored in a fixed format and fixed slot, and the

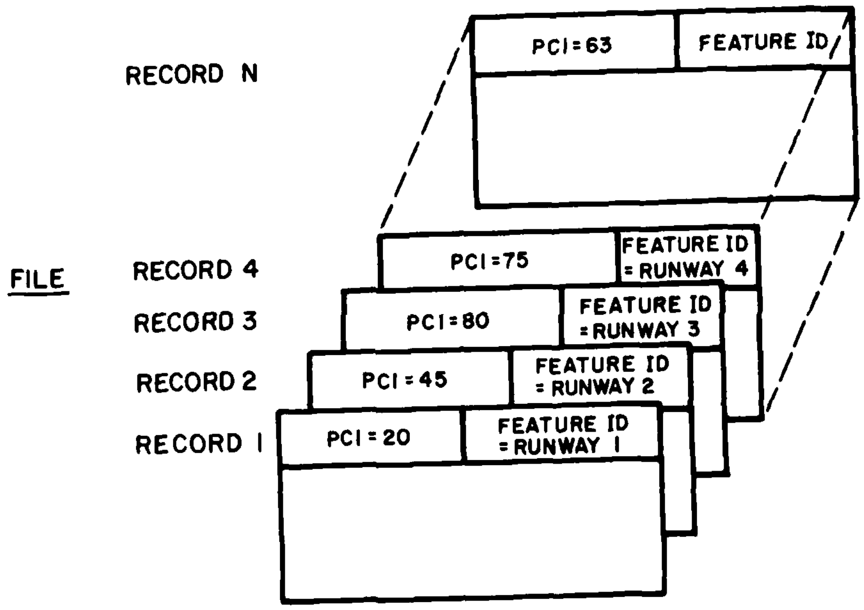

Figure 66. Sequential File.

records are stored subsequentially. Thus, to search for a record containing a certain value of a certain data item, such as PCI, each record is accessed sequentially. The search process is very slow in the sequential organization. The index sequential method (Figure 67) is like the sequential method, except that it contains an index which lists all the records which contain a specific data item, and contains the record ID. All entries in this file are arranged for fast access. Thus, the search process now searches the index instead of the entire data base. Since the index entries are arranged in order, a binary chop method can be used to find the record having a given item value. (In the binary chop method, the wanted value is compared with the value in the entry which is in the middle of the index file. If the wanted value is higher, the bottom half of the index file is discarded and the process is repeated, using the top half of the index; if the wanted value is lower, the top half of the index file is discarded and the process is repeated, using the bottom half of the index.)

The search is very fast when the index is the data item for which the search is intended. The disadvantage of the index sequential method is the need to keep both the index and the data base. A logical adaptation of the sequential or index sequential methods is use of the record to store data related to a given feature. Features of a command-level data base are sorted by base. Within a given base, records are arranged by facility.

In the "tree" organization (structures) of data (Figure 68), the top of the data base is the root of the tree (zero level). Main branches from the root are the first level, and the smaller branches connected to these are the second level. There can be as many levels as required in the data base. The advantages of the tree-type structure are: (1) space efficiency, because a branch's data items are stored only once, but can be used by all lower-level branches connected to that branch, and (2) access to the lower-level branches is faster, because each level is connected directly to the next. An example of using "tree" structure can be found in PAVER (Reference 14). In the PMIS, a logical construction of the command-level data base will assign facilities as the first-level branches, features as the second level, and data items, such as PCI and work record, as the third level.

The graph method is practically the same as the tree method, except there are connections among the branches. The advantages of the graph structure are that it is fast, and it provides simplified access to data located in multiple branches.

Data Access. The user can access the data in the data base either by writing a computer program for the specific data base under consideration, or via a readily available package (DBMS). A DBMS should be used to develop PMIS, because it is less expensive. Most commercially available DBMS systems will contain three components: the data base definition language (schema), the query language, and the interface to other languages. The data definition language defines the data base structure. The query language is useful for retrieving data based on a given criterion. The interface to other language allows a user-written program to access the data base.

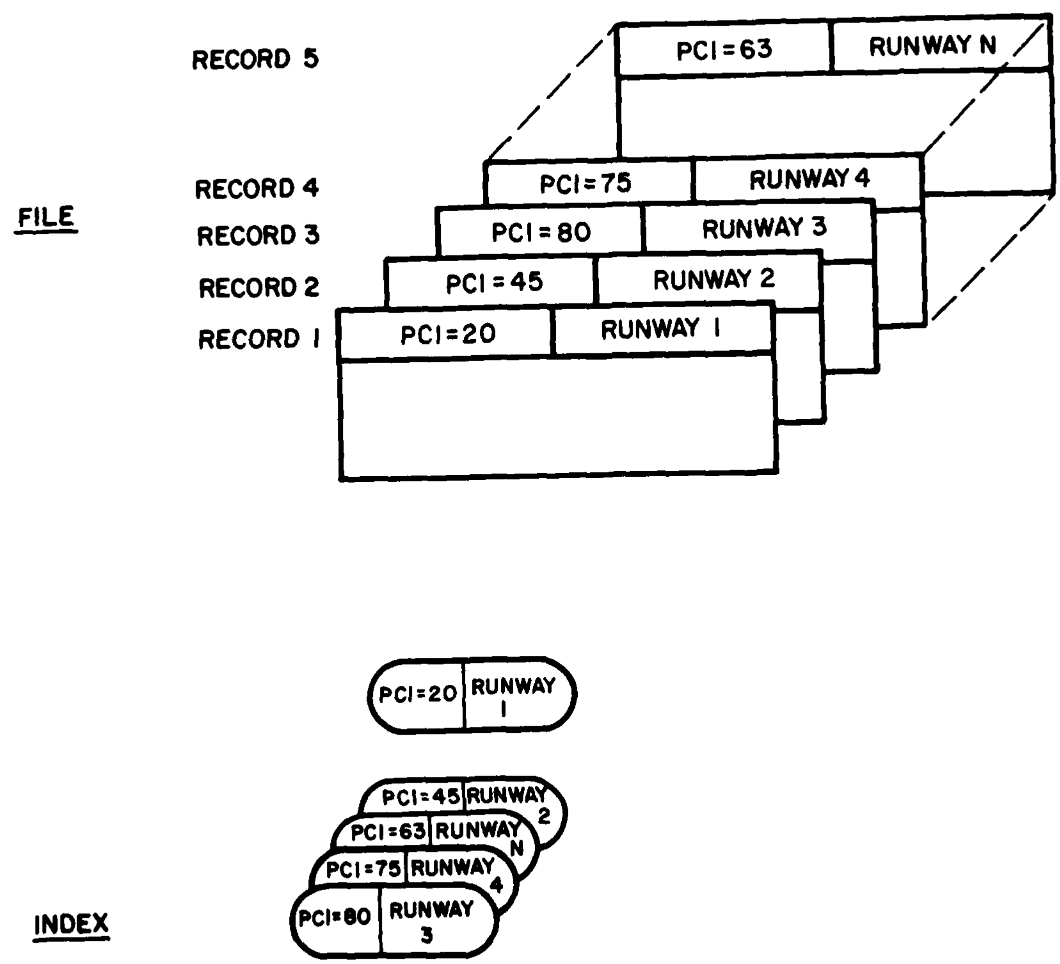

Figure 67. Index Sequential File.

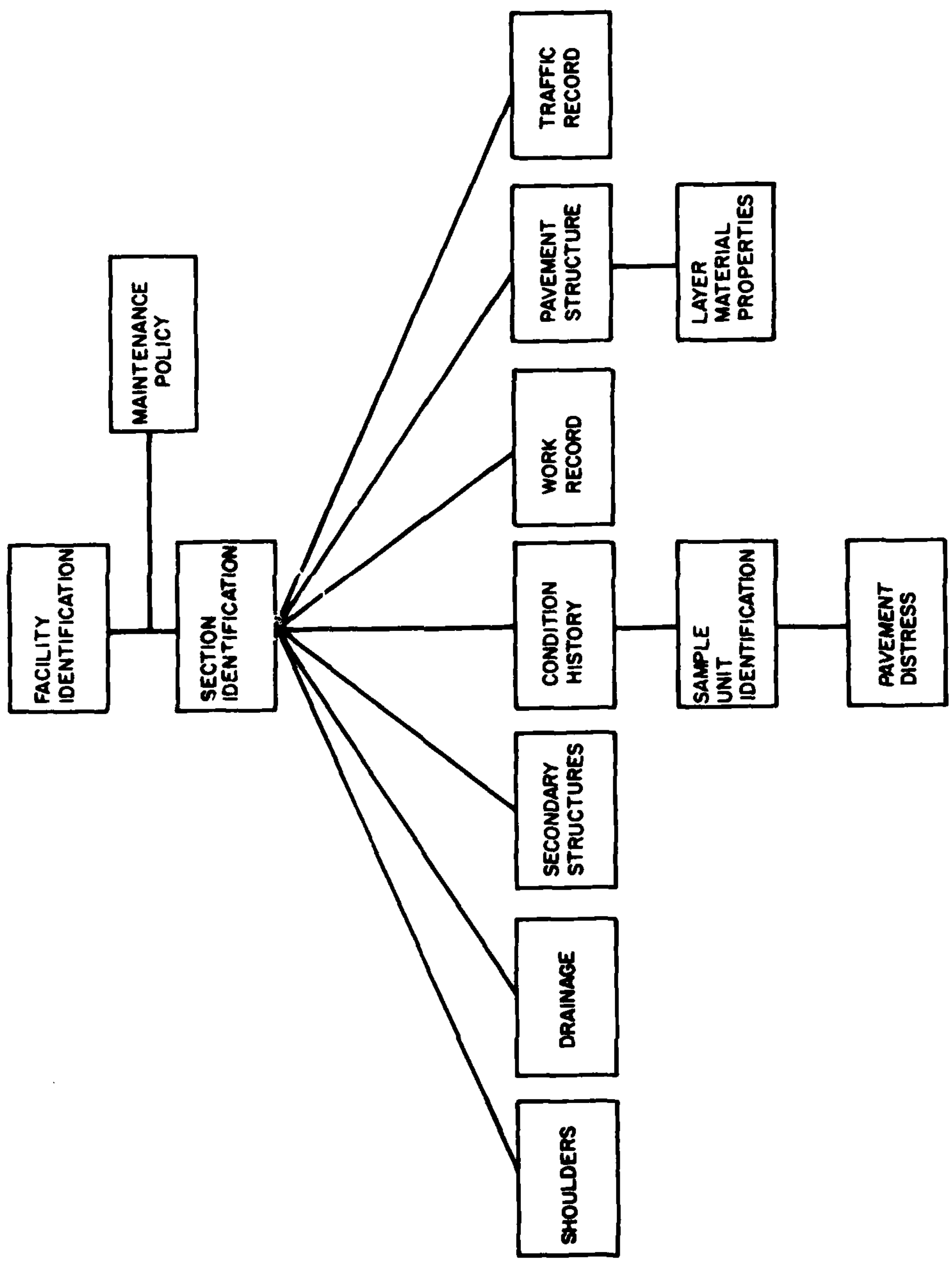

Figure 68. Tree Structure File.

Figure 68. Tree Structure File.

Since the PMIS functions are not defined completely, using the query language for data base access and report generation is better than using standalone computer programs. Thus, the type of DBMS selected depends heavily on the available functions of its query language. Most commerical DBMS query languages support logical operations. However, the various systems differ. The logical operation should be able to operate on different branches. For example, in PAVER, where a tree structure is used, the "AND" operation of a certain PCI value and a certain repair record of feature cannot be specified using the query language, because they are defined as two separate branches in the data base.

SUMMARY OF COST ANALYSIS

The PMIS may be implemented on existing Air Force machines, timesharing computer service from vendors, or a dedicated minicomputer. Since cost data for the Air Force software development and the computer operation are not available, the cost analysis will be restricted to comparing subscription to service and use of a dedicated minicomputer.

It is estimated that the entire Air Force pavement maintenance data base can be placed in a minicomputer with a 200-mega-byte disk. Such a system can support up to 32 users accessing the data base simultaneously and process the data for report generating within a suitable response time. Many minicomputers currently have a good DBMS available which is directly supported by the manufacturer or a third-party software house. Thus, the cost of software development on the dedicated minicomputer is similar to the cost of using available services. The difference is between the cost of hardware and the recurrent operation cost. Although hardware costs to support PMIS vary among vendors, a typical system costs approximately $100,000. The operation and maintenance costs of such a system range from 15 to 25 percent of the system purchase price per year.

A large-scale timeshare system will generally cost approximately $20 per hour of terminal use; this cost includes all necessary computer time and storage.

Figure 69 compares the costs of implementing the PMIS when using either (1) a dedicated minicomputer, or (2) a time-sharing system. The figure was based on costs presented in Appendix C. The costs associated with developing and operating a PMIS are divided into four major categories: (1) computer system, (2) PMIS software development, (3) system operations, and (4) software maintenance. In a time-sharing system, the computer system cost is eliminated; however, the system operating cost includes an hourly charge. Therefore, in computing the costs for the time-sharing system, the number of hours was determined based on the following assumptions: (1) each base will use the PMIS 1/2 hour per week, (2) each command will use the PMIS 2 hours per week, and (3) on the average, 10 bases per command will use the system. These assumptions result in approximately 365 hours per command per year. In addition, it was assumed that during the first year of PMIS implementation, only one command will use the system, three will use it the second year, five the third year, and 10 thereafter.

Based on these assumptions, Figure 69 shows that using a dedicated minicomputer is more economical than using a time-sharing system after 3-1/2 years of use.

Use of the PMIS system depends greatly on the base and command engineers' acceptance of the system. It is very difficult to estimate now how frequently the system will be used; however, a more accurate estimate can be made after the pilot system becomes operational.

Another factor that affects the cost of implementing a PMIS is the existence of a DBMS on the computer. It is well-documented in industry that use of a DBMS greatly reduces the cost of software development (Reference 14). The development of software for data base maintenance and general reports (which does not include the economic analysis or consequence model) with a DBMS will require only 2 man-years, while more than 10 man-years will be required for a system without a DBMS. The cost savings will be even greater when the consequence model is implemented and the economic analysis performed. Therefore, a system with a good DBMS should be used for the PMIS.

SUMMARY

Based on the available data and discussions between Air Force personnel and the CERL staff, the following directions and procedures regarding implementation of an Air Force PMIS are recommended:

1. Computer program modules similar to those used for PCI computation should be implemented on the standard Air Force base computer.

2. The data items should be refined before PMIS is fully implemented. This can only be accomplished by pilot testing the system at a selected command.

3. It will be desirable to verify and refine the proposed economic analysis and pavement condition forecasting models while the PMIS is being developed.

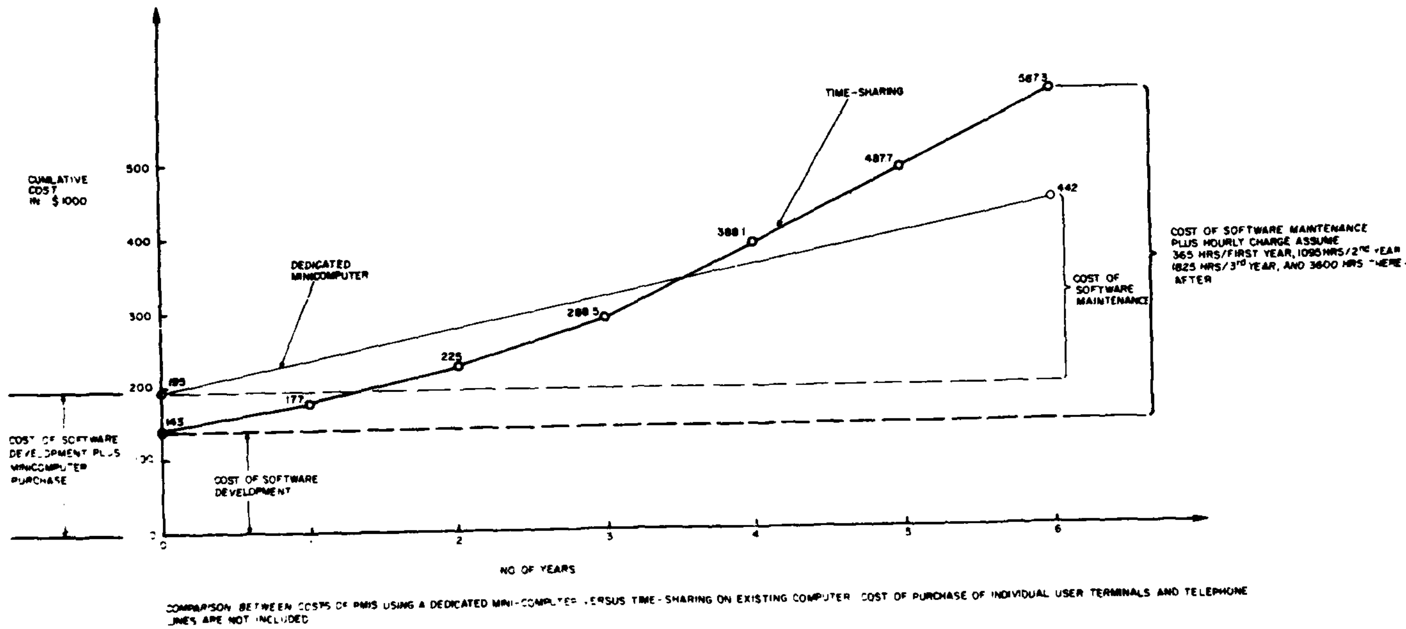

Figure 69. Comparison Between Implementation Costs of PMIS Using a Time-Sharing System and a Dedicated Minicomputer (Costs of Telephone Lines and User Terminals Are Not Included).

SECTION VIII

PART II: CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

1. The following report and computation requirements by command and base engineers for use in pavement management have been tentatively identified (subject to field testing).

a. Project validation

b. Determination of the consequences of various M&R alternatives and mission changes

(1) Economic analysis

(2) PCI determination

(3) PCI and distress prediction

(4) Load-carrying capacity

c. Project estimating

d. Annual and 5-year work planning

e. Evaluation reports

f. Visitation of bases by command engineers

g. Project priorities

h. Optimization of limited budget spending.

The expected data requirements and frequency of use of each report by command and base engineers have been identified (see Table 29).

2. Most of the report requirements listed above can be computerized and operated in a batch mode, except the M&R consequence and economic analysis requirements, which should be operated in an interactive mode.

3. The advantages and disadvantages have been identified for the following PMIS data base organizations: (1) locating the data base at the base level, (2) at the command level, or (3) at one central place for the entire Air Force. Based on available information, it is concluded that the centralized data base at the command level is probably the best data base organization (subject to field testing).

4. A limited cost performance analysis indicated that adopting one of the commercially available DBMS for use with the PMIS is more economical than developing a new one.

RECOMMENDATIONS

1. Computer modules similar to the PCI computer program should be developed for determining M&R consequences and performing economic analysis; these modules should be used with a standard Air Force base computer.

2. Information requirements for pavement management should be refined through pilot testing of the proposed PMIS, preferably on a major command computer.

3. The PMIS pilot test should also be used to evaluate the data base organization (e.g., at base level, command level, or central location) associated with the PMIS and the PMIS mode of operation (i.e., batch, interactive, or combination).

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APPENDIX A

CONCRETE PAVEMENT DATA

TABLE A-1. SUMMARY OF DATA FOR CONCRETE PAVEMENT WITHOUT OVERLAY

AFB	FEATURE	PCI	AGEOR	AGEOL	THICK	THICKOL	BASI	MR	K	JSL	JSS	ACWGT	AREA	P/S	FEAT	ZONE	FI	PPT	SR	PEI	TEMP	FAT	ACOL	PCOL	PATCH	CRK
Langley	R8C6	84	17	0	16	0	0	800	90	12.5	12.5	60	3	1	3	4	0	40	8.6	75	60	21	0	0	0.9	11.0
	R6C1	77	11	0	10	0	0	800	90	12.5	12.5	60	3	1	3	4	0	40	0	34	60	43	0	0	3.3	5
	R6C2	78	19	0	10	0	0	800	90	12.5	12.5	60	3	1	3	4	0	40	6.5	34	60	43	0	0	3.9	6.8
	R5B1	79	11	0	11	0	0	800	90	12.5	12.5	60	3	1	3	4	0	40	5	40	60	37	0	0	0	0
	R18B	88	23	0	11	0	0	800	90	25	25	60	2	1	1	4	0	40	48.8	40	60	37	0	0	0	7.1
	A1B	80	15	0	16	0	8	800	175	25	25	60	2	1	1	4	0	40	0	82	60	19	0	0	0	10
	A2C	68	15	0	11	0	6	660	100	25	25	60	3	2	2	4	0	40	0	34	60	44	0	0	0	5.6
	A17B	66	16	0	16	0	8	800	175	25	25	60	2	1	1	4	0	40	0	80	60	19	0	0	19	12
	A9B	59	21	0	15	0	0	750	100	25	25	60	2	2	1	4	0	40	0	66	60	23	0	0	0	25
	A10B	62	16	0	15	0	0	660	100	25	25	335	2	2	1	4	0	40	0	56	60	26.7	0	0	2	25
	A14B1	97	7	0	16	0	0	800	90	12.5	12.5	60	2	1	1	4	0	40	0	75	60	20	0	0	0.4	0
	R4A1	77	11	0	11	0	0	800	90	12.5	12.5	60	2	1	3	4	0	40	14.0	40	60	37	0	0	1.0	0
	R3B	82	17	0	16	0	0	800	150	15	12.5	60	2	1	3	5	0	40	13.5	83	60	19	0	0	1.7	0.8
	T1A	78	17	0	16	0	8	800	175	25	25	60	2	1	2	4	0	40	0	79	60	19	0	0	0	4
	T2A	97	2	0	16	0	6	700	150	25	25	60	2	1	2	4	0	40	0	69	60	22	0	0	0	0
	T4C	73	21	0	13.5	0	0	800	90	25	12.5	60	2	1	2	4	0	40	0	57	60	27	0	0	7.4	8.6
	T10A	84	4	0	16	0	6	700	150	25	25	60	2	1	2	4	0	40	0	69	60	22	0	0	0	12.5
	T21C	78	5	0	9	0	0	650	90	15	15	60	3	2	2	4	0	40	0.1	22	60	63	0	0	0	13
	T38A	61	16	0	16	0	8	800	100	25	25	60	2	1	2	4	0	40	0	76	60	21	0	0	3.3	13
	T39A	85	2	0	16	0	6	800	150	25	25	60	2	1	2	4	0	40	0	80	60	20	0	0	0	4.3
Barksdale	#31	66	25	0	16	0	0	700	125	25	25	335	2	1	1	7	0	47	0	68	66	55	0	0	0.2	24
Wright Patterson	T7C	60	16	0	15	0	24	760	350	25	25	490	1	1	2	1	100	37	0	76	52	59	0	0	1.9	41
	R6B	82	16	0	18	0	24	760	350	25	25	490	1	1	3	1	100	37	0	118	52	43	0	0	0	0
	T2A	77	16	0	19	0	24	760	350	25	25	490	1	1	2	1	100	37	0	128	52	39	0	0	0	5
	A14B	74	16	0	18	0	24	760	350	25	25	490	2	1	1	1	100	37	0	118	52	43	0	0	0	0
George	T5B	73	20	0	11	0	[illegible]	585	140	15	12.5	60	2	1	2	9	0	3.5	0	32	62	48	0	0	4.9	0
	T16C	46	22	0	11	0	[illegible]	695	150	25	25	60	3	2	2	9	0	3.5	0	38	62	41	0	0	0	24
McGuire	R7A	41	23	0	16	0	[illegible]	520	250	25	20	300	1	1	3	1	400	42	0	70	54	59	0	0	14	33
	TWCT	36	25	0	16	0	[illegible]	600	123	25	20	300	1	1	2	1	400	42	0	73	54	59	0	0	7.2	47
	T11B	67	20	0	7.5	0	[illegible]	[illegible]	350	20	12.5	60	2	2	2	1	400	42	0	24	54	69	0	0	0.75	21.2

TABLE A-1. SUMMARY OF DATA FOR CONCRETE PAVEMENT WITHOUT OVERLAY (CONTINUED)

AFB	FEATURE	PCI	AGLOR	AGLOL	THICK	THICKOL	BASE	MR	K	JSL	JSS	ACWGT	AREA	P/S	FEAT	ZONE	FI	PPT	SR	PEI	TEMP	FAT	ACOL	PCOL	PATCH	CRK
Williams	T8C	56	33	0	6	0	0	675	60	15	12.5	20	3	2	2	9	0	7	0	13	69	44	0	0	3.3	40
	A1B	46	33	0	6	0	0	675	60	15	12.5	20	2	1	1	9	0	7	0	13	69	44	0	0	0	61
	R1B	93	6	0	11	0	0	605	50	20	20	20	2	1	3	9	0	7	0	28	69	19	0	0	0	0
Hill	C-5 Apron	95	3	0	13	0	0	860	500	25	25	175	2	2	1	3	325	19	0	103	51	42	0	0	0	0
	Airfreight Apron	65	15	0	13	0	22	922	500	25	25	175	2	1	1	3	325	19	0	109	51	40	0	0	19	3.1
	Operational Apron	76	19	0	14	0	21	690	500	25	25	60	2	1	1	3	325	19	0	93	51	23	0	0	13	0.3
Vance	24C	71	34	0	6	0	6	800	125	20	12.5	20	2	1	2	6	0	26	15.8	17	59	34.7	0	0	0	19
	24B	75	34	0	6	0	6	800	125	20	12.5	20	2	1	1	6	0	26	7.6	17	59	34.7	0	0	0.6	13
	24A	61	34	0	6	0	6	800	125	20	12.5	20	2	1	2	6	0	26	23.5	17	59	34.7	0	0	0	24
	24D	58	34	0	6	0	6	800	125	20	12.5	20	2	1	2	6	0	26	2	17	59	34.7	0	0	0	37
	25A	55	34	0	6	0	6	800	125	20	12.5	20	2	1	1	6	0	26	7	17	59	34.7	0	0	0.3	36
	25B	62	34	0	6	0	6	800	125	20	12.5	20	2	1	1	6	0	26	19.6	17	59	34.7	0	0	0.6	30
	25C	65	34	0	6	0	6	800	125	20	12.5	20	2	1	1	6	0	26	12.5	17	59	34.7	0	0	0	30
	26	86	20	0	10	0	6	800	125	25	25	20	2	1	1	6	0	26	0	37	59	15.4	0	0	0	25
	27	71	26	0	10	0	6	800	125	20	12.5	20	2	1	1	6	0	26	0	37	59	15.4	0	0	0	0
	T5B	78	20	0	10	0	6	800	125	15	12.5	20	3	2	2	6	0	26	0	37	59	15.4	0	0	0	29
	R7B	48	20	0	10	0	6	800	125	25	25	20	2	1	3	6	0	26	0	37	59	15.3	0	0	0	28
	R10B	77	19	0	10	0	6	775	125	20	20	20	2	1	3	6	0	26	0	35	59	15.7	0	0	0	28
	R13B	71	20	0	9	0	6	750	125	25	25	20	2	1	3	6	0	26	0	29	59	19.6	0	0	0	38
	R11C	74	19	0	10	0	4	775	125	20	20	20	3	1	3	6	0	26	0	35	59	15.7	0	0	0	8
	R12C	75	20	0	10	0	6	750	125	25	25	20	3	1	3	6	0	26	0	34	59	16.3	0	0	1	28
	R14B	67	34	0	6	0	6	800	125	20	12.5	20	2	1	3	6	0	26	22	17	59	33.8	0	0	0	0
	R2B	53	20	0	9	0	6	750	125	25	25	20	2	1	3	6	0	26	0	29	59	19.6	0	0	1	83
	R6C	58	20	0	10	0	4	775	125	25	25	20	3	1	3	6	0	26	0	35	59	15.7	0	0	0	71
Ellsworth	R17B	89	16	0	22	0	25	665	160	25	25	490	1	1	3	3	678	18	0	64	46	40	0	0	1.3	2.5
	R15C	73	17	0	18	0	12	750	125	25	25	490	3	1	3	3	678	18	0	80	46	50	0	0	13	0
	R14C	73	17	0	18	0	15	750	125	25	25	490	3	1	3	3	678	18	0	80	46	50	0	0	13	0
	R12C	69	17	0	18	0	9	750	110	25	25	490	3	1	3	3	678	18	0	79	46	50	0	0	5.6	1.9
	R4B	80	21	0	19	0	4	650	30	25	25	490	1	1	3	3	678	18	0	83	46	62	0	0	0	0
	R3A	79	21	0	22	0	4	650	60	25	25	490	1	1	3	3	678	18	0	91	46	46	0	0	0	1.3

TABLE A-1. SUMMARY OF DATA FOR CONCRETE PAVEMENT WITHOUT OVERLAY (CONCLUDED)

AFB	FEATURE	PCI	AGEOR	AGEOL	THICK	THICKOL	BASE	MR	K	JSL	JSS	ACWGT	AREA	P/S	FEAT	ZONE	FI	PPT	SR	PEI	TEMP	FAT	ACOL	PCOL	PATCH	CRK
Shaw	T99-A	78	15	0	9	0	0	600	150	25	12.5	60	2	1	2	7	0	45	0	25	64	64	0	0	6.8	5.2
	T12A	57	25	0	8	0	0	675	150	20	12.5	60	2	1	2	7	0	45	0	17	64	69	0	0	3.8	31
	A5B	54	21	0	9	0	0	600	150	25	12.5	60	2	1	1	7	0	45	0	25	64	64	0	0	3.3	42
	R1A/R2B	70	18	0	9	0	0	600	175	15	12.5	60	2	1	3	7	0	45	0	24	64	63	0	0	0	1.5
Homestead	R/W int	84	14	0	13	0	0	725	500	25	25	60	2	1	3	7	0	56	0	87	75	25	0	0	0	0
Travis	TW 30	65	6	0	15	0	6	650	200	25	25	300	1	1	2	6	0	18	0	62	58	55	0	0	1.2	38.9
	400 RAMP	48	18	0	10	0	12	750	200	20	12.5	300	2	1	1	6	0	18	0	37	58	80	0	0	8.1	40.5

TABLE A-2. SUMMARY OF DATA FOR CONCRETE PAVEMENT WITH CONCRETE OVERLAY

AFB	FEATURE	PCI	AGEOR	AGEOL	THICK	THICKOL	BASE	MR	K	JSL	JSS	ACWGT	AREA	P/S	FEAT	ZONE	FI	PPT	SR	PLI	TEMP	FAT	ACOL	PCOL	PATCH	CRK
Langley	A12B	60	36	23	6	9	0	725	120	15	12.5	60	2	1	1	4	0	40	5.6	63	60	24	0	9	20	48
	A14A	81	36	12	8	8	0	715	130	12.5	12.5	60	2	2	3	4	0	40	14	70	60	26.7	0	8	0	1.4
	T13A	73	37	12	6	10	0	710	90	15	12.5	60	2	1	2	4	0	40	0	65	60	23	0	10	34	13
Barksdale	#13	70	33	23	19	8	0	700	90	15	12.5	490	2	1	1	7	0	47	0	64	66	51.6	0	8	3	56
Williams	T12C	90	22	16	15	8	0	800	60	15	15	20	3	1	3	9	0	7	0	63	69	11	0	8	0	0

[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	ACWGT	AREA	[illegible]	FEAT	[illegible]	[illegible]	PPT	SR	PEI	TEMP	FAT
Wright Patterson	[illegible]	[illegible]	[illegible]	4	4	[illegible]	[illegible]	[illegible]	200	15	12.5	60	3	[illegible]	2	1	[illegible]	37	0	0	52	39
	R30	60	21	4	11	4	30	650	350	15	12.5	490	3	1	3	1	100	37	0	0	52	28
	A10B	74	23	4	10	2.5	6	770	235	15	12.5	60	2	1	1	1	100	37	0	0	52	37
	[illegible]	71	32	5	10	2	6	650	200	15	12.5	60	3	2	2	1	585	37	0	0	52	35
Scott	T58	76	21	7	11	2	[illegible]	640	70	30	12.5	110	1	1	2	4	0	40	0	0	55	65
	R33	60	34	7	6	[illegible]	15	690	70	25	20	110	3	1	3	4	0	40	0	0	55	78
Williams	T2AC	78	33	21	6	3	0	675	60	15	12.5	20	3	2	2	9	0	7	0	0	69	34
Barksdale	RW100-00	80	23	13	16	3	0	700	100	25	25	490	3	1	3	7	0	47	0	0	66	51
Shaw	R40	77	30	13	6	2	0	600	300	15	12.5	60	3	1	3	7	0	45	0	0	64	92
	R50	68	26	11	7	2	0	650	300	15	12.5	60	3	1	3	7	0	45	0	0	64	71
	R60	81	25	12	6	2	0	750	300	15	12.5	60	3	1	3	7	0	45	0	0	64	51
Hill	TAXI 3	63	37	6	6	2	9	650	150	25	25	60	2	1	2	3	325	19	0	0	51	96
	TAXI IN	49	37	6	6	2	9	650	150	25	25	60	2	1	2	3	325	19	0	0	51	96
	TAXI IC	48	37	8	6	2	9	650	150	25	25	60	2	1	2	3	325	19	0	0	51	96
Ellsworth	R70	68	21	11	17	2.5	4	650	60	25	25	490	3	1	3	3	678	18	0	0	42	66
	R90	34	17	[illegible]	17	4	18	750	160	25	25	490	3	1	3	3	678	18	0	0	42	47
Elmendorf	41	37	35	6	6	1.5	0	670	300	15	12.5	175	2	2	1	3	2070	15	0	0	31	161
	42	64	33	10	6	1.5	[illegible]	670	500	20	20	175	2	2	1	3	2070	15	0	0	31	153
Langley	T10A	64	23	11	10	2	0	300	90	15	12.5	60	2	1	2	4	0	40	0	0	60	40

APPENDIX B

ASPHALT PAVEMENT DATA

TABLE B-1. ASPHALT PAVEMENT DATA (NO OVERLAY)

AFB	FEATURE	PCI	AGEOR	AGEOL	T.A.C. THICK	B THICK	SB THICK	B CBR	SB CBR	SG CBR	ACWGT	AREA	P/S	FEAT	ZONE	FI	PRECI	AA TEMP	ADTR	AATR	% AC	% SG	T EQUIV THICK	% EQUIV THICK
Pope	R4C	81	15	0	6.5	8	0	24	0	21	175	3	1	3	4	0	47	60.8	19.4	36.5	.468	.9152	19.1	1.2287
	R6C(A)	51	23	0	5	11	0	24	0	24	175	3	1	3	4	0	47	60.8	19.4	36.5	.381	1.121	19.5	1.3477
	R6C(B)	81	23	0	7.5	11	0	24	0	24	175	3	1	3	4	0	47	60.8	19.4	36.5	.525	1.2844	23.8	1.6215
	T14B	36	35	0	5	9	0	40	0	35	175	1	2	2	4	0	47	60.8	19.4	36.5	.544	1.252	17.5	1.5532
McGuire	R/W 18-36	20	14	0	3	10	16	80	40	10	325	3	2	3	1	400	42	53.5	19.6	43.3	.341	.883	35.3	1.0178
	R/W Main	45	13	0	3	12	9	80	45	38	325	3	1	3	1	400	42	53.5	19.6	43.3	.409	1.801	33.6	2.0346
Williams	R2C	86	5.5	0	4	6	8	60	22	10	21	3	1	3	9	0	7	69	31.4	40.1	.614	1.7877	20.8	2.0599
	R4C	100	0.5	0	4	4	8	100	80	10	21	3	1	3	9	0	7	69	31.4	40.1	.878	1.5878	26.0	2.5749
	T7B	70	9	0	3.5	6	9	40	20	10	21	3	2	2	9	0	7	69	31.4	40.1	.425	1.8395	21.0	2.0797
Vance	T14B	72	21	0	3	6	11	80	40	7	21	2	1	2	6	0	28	60	21.1	45.9	1.0117	1.6310	24.5	1.9980
	T14B	89	21	0	5	6	11	56	40	7	21	2	1	2	6	0	28	60	21.1	45.9	1.3001	1.7941	27.9	2.2753
	T15A	58	21	0	3	13	7	80	18	7	21	2	1	2	6	0	28	60	21.1	45.9	1.0117	1.8757	29.3	2.3895
	T/W 1	81	21	0	3	13	7	80	18	7	21	2	1	2	6	0	28	60	21.1	45.9	1.0117	1.8757	29.3	2.3895
	T3B	80	21	0	3	13	7	80	30	7	21	2	1	2	6	0	28	60	21.1	45.9	1.0117	1.8757	29.3	2.3895
	T3B	77	21	0	3	13	7	80	30	7	21	2	1	2	6	0	28	60	21.1	45.9	1.0117	1.8757	29.3	2.3895
	T15B	83	21	0	4.5	12	5	62	18	7	21	2	1	2	6	0	28	60	21.1	45.9	1.2528	1.7534	27.1	2.2101
Homestead	TR-5	53	20	0	4	6	0	80	0	80	60	2	1	1	7	0	56	75.1	16	15.4	.741	1.853	15.2	2.8158
	TR-9	43	20	0	4	6	0	80	0	80	60	2	2	1	7	0	56	75.1	16	15.4	.741	1.853	15.2	2.8158
	Par T/W	52	20	0	4	6	0	80	0	80	60	2	2	1	7	0	56	75.1	16	15.4	.741	1.853	15.2	2.8158
Elmendorf	T/W #8	63	19	0	4	6	0	80	0	50	325	1	1	2	3	2070	15	35.8	15.3	46.1	.542	.9414	15.2	1.3412
Ellsworth	T22B	12	27	0	4	12	28	80	45	5	490	1	1	2	3	678	18	46.1	24.6	51.2	.4076	.7193	51.6	.8183
	T16A	27	27	0	4	12	28	80	35	6	490	1	1	2	3	678	18	46.1	24.6	51.2	.4076	.7899	51.6	.8983
Scott	A4B	29	11	0	2	6	18	100	20	6	110	2	1	2	4	0	40	55.3	20.6	46.2	.4652	.8544	29.3	.9561
	A4B(A)	67	11	0	2	6	18	100	20	6	110	2	2	1	4	0	40	55.3	20.6	46.2	.4652	.8544	29.3	.9561
Travis	R/W 32-21R	74	8	0	4	27	24	80	23	4	325	3	1	3	6	0	18	60.4	26.4	30.2	.5376	.8783	65.0	1.0108
Hill	T/W 1	69	21	0	4	6	24	100	100	20	60	1	1	3	5	325	19	51.3	25.2	50.1	.8778	2.8295	36.8	3.0625

TABLE B-2. ASPHALT PAVEMENT DATA WITH AC OVERLAY

AFB	FEATURE	PCI	AGEOR	AGEOL	T.A.C. THICK	B THICK	SB THICK	B CBR	SB CBR	SG CBR	ACWGT	AREA	P/S	FEAT	ZONE	FI	PRECI	AA TEMP	ADTR	AATR	AC	SG	T EQUIV THICK	EQUIV THICK	AGE COL	ACOL THICK
Pope	R2B	51	34	9	6	8	0	24	0	21	175	3	1	3	4	0	47	60.8	19.4	36.5	.429	.9152	18.2	1.1764	25	3
	R3C	57	34	9	6	8	0	24	0	21	175	3	1	3	4	0	47	60.8	19.4	36.5	.429	.9152	18.2	1.1764	25	3
	R5C	64	34	9	8.5	16.5	0	40	0	20	175	3	1	3	4	0	47	60.8	19.4	36.5	.910	1.527	31.0	1.8313	25	3
George	T26B	36	22	9	5	6	4	40	20	5	60	2	1	2	9	0	3.5	63.9	29.4	35.2	.607	.588	18.5	.7256	13	2
McGuire	A11B	17	35	23	2.5	4	8	50	40	16	60	2	2	1	1	40	42	53.5	19.6	43.3	.526	1.106	18.3	1.3495	12	0.5
Eielson	TW#6	45	32	10	7.5	9	0	50	0	50	335	2	1	2	3	5320	11	25.8	22.8	60.8	.736	1.4618	21.8	1.8324	22	1.5
	R/W N-S	63	30	10	8	9	0	45	0	50	335	3	1	3	3	5320	11	25.8	22.8	60.8	.736	1.4944	22.6	1.8760	20	1.5
Ellsworth	T2A	65	22	6	9	6	42	30	55	8	490	1	1	2	3	678	18	46.1	24.6	51.2	.8912	1.1231	65.7	1.2641	16	5
Scott	R4B	53	24	7	12	6	6	40	15	6	110	2	1	3	4	0	40	55.3	20.6	46.2	.2771	.8036	32.4	1.0218	17	2
	T13B	88	19	4	5	10	6	100	60	6	110	1	1	2	4	0	40	55.3	20.6	46.2	.1415	.7169	26.5	.8708	15	2
Hill	R/W 32	86	21	7	6.5	6	24	100	100	20	60	3	1	3	3	325	19	51.3	25.2	50.1	.4263	3.0375	41.1	3.4203	14	2.5

TABLE B-3. ALLIGATOR CRACKING AND PATCHING DENSITY (PERCENT) (NO OVERLAY)

AFB	Feature	Alligator Cracking Low	Medium	High	Total	Patching
Pope	R4C	1.13	0	0	1.13	0
	R6C(A)	3.01	4.59	0	7.6	0.49
	R6C(B)	0.36	0.03	0	0.39	0
	T14B	0	0	0	0	0
McGuire	R/W 18-36	5.79	15.57	0	21.36	0.6
	R/W Main	10.2	3.67	0	13.87	0.53
Williams	R2C	0.03	0	0	0.03	0
	R4C	0	0	0	0	
	T7B	0	0	0.4	0.4	0
Vance	T14B	0.92	0.14	0	1.06	0
	T14B	0	0	0	0	0
	T15A	2.28	2.56	0	4.84	0.3
	T/W 1	0.16	0	0	0.16	0
	T3B	0.60	0	0	0.60	0
	T3B	0.64	0	0	0.64	0
	T15B	0.51	0	0	0.51	0.16
Homestead	TR-5	3.30	0	0	3.30	0
	TR-9	0	0	0	0	0
	Par T/W	7.04	0	0	7.04	0.16
Elmondorf	T/W#8	0.23	0	0	0.23	.13
Ellsworth	T22B	0.24	43.64	6.94	50.82	0.10
	T16A	5.19	24.04	0.5	29.73	0.03
Scott	A4B	1.3	30.5	0	31.8	0
	A4B(A)	0	0	0	0	0
Travis	R/W 36-21R	0.72	0.15	0	0.87	0.56
Hill	T/W 1	0.07	0	0	0.07	0.46

TABLE B-4. ALLIGATOR CRACKING AND PATCHING DENSITY (PERCENT) (OVERLAY)

AFB	Feature	Alligator Cracking				Patching
		Low	Medium	High	Total	
Pope	R2B	6.13	4.47	0	10.60	0
	R3C	0.60	0.89	0.15	1.64	0
	R5C	0	4.0	0	4.0	0.02
George	T26B	3.48	6.55	0	10.03	4.73
McGuire	A11B	1.38	25.12	0.03	26.53	2.66
Eielson	T/W#6	0.93	2.43	0.31	3.67	0.83
	R/W N-S	0.18	0	0	0.18	0
Ellsworth	T2A	0.50	0.50	0	1.0	0
Scott	R4B	3.15	0.75	0	3.90	0.85
	T13B	0.32	0.01	0	0.33	0.15
Hill	R/W 3C	0.09	0	0	0.09	0.05

APPENDIX C

DETAILED COST ANALYSIS OF PMIS DEVELOPMENT AND OPERATION

The costs associated with the development and operation of a PMIS are divided into four major categories: (1) computer system, (2) PMIS software development, (3) system operations, and (4) software maintenance. Because of its reliability and flexibility, the Modular Computer System (MODCOMP) CLASSIC computer was chosen to compare using a dedicated minicomputer with subscribing to a commercial time-sharing service. The MODCOMP CLASSIC has a widely used data base management package (TOTAL), and commonly used high-level computer languages such as COBOL and FORTRAN.

The commercial time-sharing system chosen was the Naval CDC Cyber computer system, which is available from Washington, D.C. The System 2000 data base management package used in PAVER is available on the Cyber machine.

The following outlines the costs of the two options.

DEDICATED MINICOMPUTER

One Time Cost:

Hardware Purchase....................................	$ 99,950
Software Development.................................	$103,000

Recurrent Cost (per year):

Operation..	$ 20,600
Software Maintenance.................................	$ 20,600

<u>Costs of Computer System</u>

MODCOMP CLASSIC 7860 with 256 k-byte memory............................	$ 40,000
50 mega-byte moving head disk and controller...............................	$ 23,000
Terminal interface for up to 32 terminals..............................	$ 5,000
Magnetic tape (45 ips, 800 bpi)..	$ 10,200
Matrix line printer..................................	$ 3,700
16 terminals at $500 each............................	$ 8,000
TOTAL data base software.............................	$ 10,000
Subtotal...	$ 99,950

PMIS Software Development

One systems analyst (1 man-year)	$ 25,000
One programmer (1 man-year)	$ 20,000
Supporting staff (1 man-year)	$ 10,000
Overhead at 65 percent	$ 36,000
Subtotal	$ 91,000
Computer maintenance	$ 6,000
Supply	$ 3,000
Miscellaneous	$ 3,000
Subtotal	$ 12,000
Total	$103,000

Operating Cost

Computer maintenance	$ 6,000
Computer	$ 3,000
Supply	$ 3,000
1/2 FTE operator	$ 7,000
Overhead	$ 4,600
Total (recurrent cost each year)	$ 20,600

Software Maintenance at 20 Percent of Development Per Year	$ 20,600

COMMERCIAL TIME-SHARING

One-time cost:

Hardware	$ 8,000

Software development	$143,000
Recurrent cost (per year):	
Operation	$ 36,000
Software maintenance	$ 20,600

Hardware Cost

16 terminals at $500	$ 8,000

PMIS Software Development

Cost indicated in PMIS software development	$103,000
Computer service	$ 40,000
Total	$143,000

Operation Cost

Supply	$ 3,000
Miscellaneous	$ 3,000
Computer service (1500 hours/command)	$ 30,000
Total	$ 36,000

Software Maintenance	$ 20,600

INITIAL DISTRIBUTION

HQ AFSC/DEEE	6
HQ AFRES/DEMM	12
HQ ATC/DEMM	20
HQ SAC/DEMM	20
HQ USAFE/DEMO	30
HQ PACAF/DEEE	16
HQ MAC/DE	25
HQ TAC/DE	35
HQ AFESC/TST	2
HQ AFESC/DEMP	2
HQ AFESC/RDCF	13
CERF	2
DDC/DDA	2
FAA/RD430	5
HQ AAC/DEEE	5
HQ AFLC/DEMG	9
AFIT/Tech Library	1
USAWES	10
HQ AUL/LSE 71-249	1
CERL	26
ANGSC/DEM	8
AFIT/DET	2
USAFA/DFCEM	1
HQ AFESC/RDXX	1

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